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ACTIVITY OF BENZOBICYCLON HERBICIDE IN COMMON LOUISIANA RICE PRODUCTION PRACTICES

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

In

The School of Plant, Environmental and Soil Sciences

by
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Abstract

A study was conducted at the LSU AgCenter H. Rouse Caffey Rice Research Station (RRS) to evaluate benzobicyclon herbicide application timing on water-seeded rice. Benzobicyclon was applied at seven different timings, at 246 g ai ha^{-1} in a water-seeded rice production system. Benzobicyclon controlled ducksalad above 90% when applied into the pinpoint flood. Barnyardgrass control was greater than 90% from applications made on pegging rice and immediately following pinpoint flood establishment. At 49 days after treatment (DAT), yellow nutsedge control exceeded 90% following benzobicyclon treatment with a pegging rice or pinpoint flood timing. Ducksalad control was greater than 90% following application into the pinpoint flood.

A study was conducted at the RRS and LSU AgCenter Northeast Research Station (NERS) to evaluate nine different rates of benzobicyclon on weeds common to Louisiana rice production. Benzobicyclon was applied at 0, 31, 62, 123, 185, 246, 493, 739, 986, and 1232 g ha^{-1}. Barnyardgrass, yellow nutsedge, and false pimpernel did not exceed 50% control, regardless of benzobicyclon rate. At 42 DAT, benzobicyclon applied at 185 and 246 h ha^{-1} controlled purple ammannia and Indian toothcup, respectively, and this control was similar to control observed with 986 to 1232 g ha^{-1} of benzobicyclon. At the conclusion of the study, no differences in fresh weight biomass occurred for barnyardgrass, yellow nutsedge, purple ammannia, or false pimpernel. Benzobicyclon applied at 246 g ha^{-1} reduced ducksalad and Indian toothcup biomass 87 and 77%, respectively.

A glasshouse study was conducted at the LSU campus in Baton Rouge to evaluate five rates of benzobicyclon applied into a 5- or 10-cm flood. Benzobicyclon applied at 246 g ha^{-1}, in either flood depth, reduced yellow nutsedge tuber development and growth. Tuber production is the primary means of yellow nutsedge reproduction in the southern US, and use of this herbicide could impact future nutsedge populations.

A field study was conducted to evaluate benzobicyclon in mixture with imazethapyr or imazamox in imidazolinone-resistant rice. The addition of benzobicyclon increased activity on hemp sesbania over imazethapyr or imazamox; however, hemp sesbania control did not exceed 30% when treated with any herbicide mixture.

Chapter 1

Introduction

Rice (*Oryza sativa* L.) is an important grain crop produced in the United States and was planted on 1.1 million hectares in 2015. Louisiana ranked second in the U.S. in planted area with 182,000 hectares of rice in 2015 (USDA NASS 2015). Many inputs are necessary to produce a marketable rice crop, and approximately 9% of total inputs on rice are pesticides including chemical weed control (Salassi 2015). Weeds compete with rice plants for sunlight, nutrients, and other resources necessary for optimum rice growth, and competition can result in the reduction of total rough rice yield and quality (Smith 1968; 1983; 1984).

Common rice weeds encountered in Louisiana rice production include both broadleaves and grasses. Common monocot species include spreading dayflower (*Commelina diffusa* Burm. F.), red rice (*Oryza sativa* L.) barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], junglerice (*Echinochloa colona* L.), broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], Amazon sprangletop [*Leptochloa panicoides* (J. Presl) Hitchc.], and Nealley’s sprangletop (*Leptochloa nealleyi* Vasey) (Bergeron et al. 2015a; 2015b; Webster 2011). Several perennial grasses including creeping rivergrass [*Echinochloa polystachya* (Knuth) Hitch.], water paspalum (*Paspalum hydrophilum* Henr.), brook crowngrass (*Paspalum acuminatum* Raddi) and knotgrass (*Paspalum distichum* L.) can also be troublesome in Louisiana rice fields (Bottoms et al. 2011; Griffin et al. 2008; Webster 2007). Broadleaf weeds encountered in Louisiana rice fields include hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], Indian jointvetch (*Aeschynomene indica* L.), alligatorweed [*Alternanthera philoxeroides* (Mart.) Grisb.] and Texasweed [*Caperonia palustris* (L.) St. Hil.]. Troublesome sedge species occurring in rice cropping systems include yellow nutsedge (*Cyperus esculentus L.*) and rice flatsedge (*Cyperus iria* L.).

Several weed species are dependent on aquatic environments for survival and rice production in flooded conditions can aid these aquatic weeds where populations have become a nuisance in Louisiana rice fields (Webster 2014). These troublesome aquatic weeds include pickerelweed (*Pontederia chordata* L.), ducksalad [*Heteranthera limosa* (Sw.) Willd.], creeping burhead [*Echinodorus cordifolius* (L.) Griseb.], grassy arrowhead (*Sagittaria graminea* Michx. var. *graminea*), common arrowhead (*Sagittaria latifolia* Willd.), purple ammannia (*Ammannia coccinea* Rottb.), Indian toothcup [*Rotala indica* (Willd.)Koehne] and disk waterhyssop [*Bacopa rotundifolia* (Michx.) Wettst.]. Rice fields in South Louisiana are often rotated with crawfish [*Procambarus clarkii* (Girard); *Procambarus zonangulus* (Hobbs & Hobbs)] aquaculture production systems. The extended period of inundation from flood irrigation in this rotational system selects for these weed species that would otherwise not present a problem in rotations with lengthy periods of non-flooded soil conditions.

Competition between rice and weeds differs among species and duration of weed competition. Season-long grass weed competition from red rice, *Echinochloa spp*., bearded sprangletop [*Leptochloa fascicularis* var. *panicoides* (Lam.) Grey], Amazon sprangletop, and broadleaf signalgrass reduces rough rice yield 82, 70, 36, 35, and 32% respectively (Diarra et al. 1985; McGregor 1988; Smith 1968; 1974; 1983). Season-long ducksalad, hemp sesbania, spreading dayflower, and northern jointvetch competition reduced rough rice yield 21, 19, 18, and 17%, respectively (Smith 1968; 1984). Weeds also impact rough rice quality. The presence of *Ipomoea* and hemp sesbania seeds in harvested rice grain reduces grade and has a negative impact on the value of the harvested crop (Smith 1988; Smith et al. 1977).

Smith (1988) described a difference in weed complexes depending on planting practices and water management of a rice crop. Common dry-seeded weeds include barnyardgrass, sprangletop spp., eclipta [*Eclipta prostrata*

(L.)L.] and spreading dayflower. Barnyardgrass and sprangletop spp. can emerge and be competitive with rice in water-seeded systems where flood water is temporarily drained to allow for rice seedling establishment. Aquatic weeds including purple ammannia and ducksalad can emerge through a permanent flood established early in water-seeded plantings.

Both dry- and water-seeded planting practices are employed in Louisiana rice production (Harrell and Saichuk 2014). In water-seeded production three different flood systems are commonly utilized. These include the delayed flood, pinpoint flood, and the continuous flood. In the delayed flood system, fields are drained following seeding for a period of 3- to 4-weeks before the permanent flood is established. A pinpoint flood system is characterized by draining for 3- to 5-days following planting to allow for seedling establishment before the permanent flood is established. In the continuous flood system, flood water remains on the field from the time of seeding until draining for harvest (Harrell and Saichuk 2014). Approximately 35% of the planted rice area in Louisiana was water-seeded in 2016 (Harrell 2016)

Water-seeding was once the most widely utilized method of planting rice, especially in southwest Louisiana (Harrell and Saichuk 2014). Water-seeding with the pinpoint flood technique is an effective way to reduce red rice competition with cultivated rice by creating an environment that reduces red rice germination (Dunand et al. 1985; Levy et al. 2006; Sonnier and Baker 1980). The discovery and development of imidazolinone-resistant (IR) rice in 1993 provided a new means of economical chemical weed management for red rice in cultivated IR rice varieties and hybrids (Carlson et al. 2012; Croughan 1994, Webster and Masson 2001). Imidazolinone herbicides are included in a large group of herbicides that inhibit acetolactate synthase (ALS) (EC 4.1.3.18) (Shaner 2014). Imazethapyr and imazomox are two imidazolinone herbicides labeled for use in IR rice varieties and hybrids at rates of 70 to 105 g ai ha^{-1} and 35 to 53 g ai ha^{-1}, respectively (Webster 2014). In addition to red rice activity, these imidazolinone herbicides have activity on other grasses and some broadleaf weeds; however, many weeds occurring in rice fields are not controlled by these herbicides (Ottis et al. 2002; Richburg et al. 1995; Webster et al. 2012; Webster and Masson 2001; Zhang et al. 2001).

The adoption of IR rice technology broadened the flexibility of tillage and cultural practices by offering an effective means of red rice control in a drill-seeded production system (Harrell and Saichuk 2014). Despite a decrease in water-seeded plantings in recent years, this practice still has an important role in crawfish/rice rotations. Water-seeding is also the preferred means of rice seeding for producers that have grown accustomed to the method because of the convenience and reduced time of planting compared to drill seeding. Water seeding is an alternative to drill seeding when excessive rainfall inhibits timely dry planting systems.

Weed resistance to herbicides has become an increasing problem in U.S. rice production. Several examples of weed resistance have been documented in rice, beginning with resistance of barnyardgrass in Arkansas to propanil in the early 1990s (Baltazar and Smith 1994; Carey et al. 1995). Barnyardgrass with multiple resistances to both propanil and quinclorac was documented in 1999 (Malik et al. 2010), and populations of barnyardgrass have documented resistance to imazethapyr in 2008 and clomazone in 2007 in Arkansas (Norsworthy 2009; Wilson 2011). In Louisiana, barnyardgrass populations have been confirmed to have resistance to propanil, quinclorac, and imazethapyr in 1995, 1998, and 2013, respectively (Heap 2017). Amazon sprangletop resistant to cyhalofop-butyl and fenoxaprop-P-ethyl was confirmed in Louisiana in 2009. Confirmed resistance of rice flatsedge to ALS-inhibiting herbicides was documented in Arkansas and Mississippi rice fields in 2010 and Louisiana in 2013. Rotating herbicide mode of action can be an effective method for managing weed resistance to herbicides in crops. The adoption of new modes of action that currently are not labeled for use in a particular crop can also improve resistance management by controlling susceptible weed species at a different site or mode of action (Norsworthy et al. 2012).

Currently, 4-hydroxyphenylpyruvate dioxygenase (HPPD) (EC 1.13.11.27) inhibiting herbicides are not labeled for use in U.S. rice production (Webster 2016). These herbicides interfere with a key step in plastoquinone biosynthesis and the resulting symptoms are bleached plant tissue appearing on new growth (Shaner 2014). Herbicides employing this mode of action are labeled in grass crops including corn, sugarcane, cereals, and rice. Mesotrione and isoxaflutole are HPPD inhibiting herbicide, with both preemergence (PRE) and postemergence (POST) activity, labeled for use in U.S. corn production for the management of grass and broadleaf weeds (Bhowmik et al. 1999; Stephenson et al. 2004).

Benzobicyclon is a HPPD inhibiting herbicide discovered and developed by SDS Biotech in Japan (Komatsubara et al. 2009). This herbicide has been registered for use in Japan since 2001, and is available in several different forms and pre-packaged mixture combinations. Benzobicyclon is considered a pro-herbicide because it must undergo a hydrolysis reaction in the presence of water to render the active herbicide, benzobicyclon-hydrolysate. Other examples of pro-herbicides exist in the aryloxyphenoxypropionic acid, cyclohexanedione, isoxazolidinone, and sulfonylurea chemical families (Gronwald 1994; Mueller et al. 2000; O’Keefe et al. 1994). Bleaching of plant tissue is the primary symptom of herbicide injury on susceptible weed species when treated with benzobicyclon, followed by chlorosis and complete plant death (Komatsubara et al. 2009). Sekino et al. (2008) indicated both PRE and POST benzobicyclon activity on susceptible weeds at rates of 200 to 300 g ha^{-1}, and little or no phytotoxicity was observed in rice plants when applied at 600 g ha^{-1}. This research also concluded that the primary route of benzobicyclon uptake occurred via root and shoot tissue. Control of susceptible weed species was observed 8 weeks after treatment (WAT), indicating favorable residual control characteristics. When applied PRE across a variety of soil textures, little or no differences in activity were detected. Sun et al. (2016) determined benzobicyclon has a half-life of 6.7 days in soil. Williams and Tjeerdema (2016) determined that water pH, temperature, and the presence of dissolved organic carbon impact conversion of benzobicyclon to benzobicyclon-hydrolysate, and the half-life of benzobicyclon in basic conditions is 5 to 28 h. The dissipation of the active form, benzobicyclon-hydrolysate, in flooded conditions is currently not known but it was determined through this research that this form is hydrolytically stable and similar in these characteristics to mesotrione and sulcotrione.

Weed spectrum controlled with benzobicyclon application was also evaluated on common weed species occurring in rice production in Japan (Sekino et al. 2008). *Monochoria vaginalis* [(Burm. f.) C. Presl. ex Kunth], *Schoenoplectus juncoides* [(Roxb.) Palla], barnyardgrass, *Cyperus serotinus* (Rott.), *Sagittaria pygmaea* (Miq.), and *Lindernia dubia* [(L.) Pennell var. dubia] were treated with 200, 300, and 600 g ha^{-1} at PRE, one-leaf, and two-leaf application timings. All weed species were controlled 90% or greater with a PRE 200 g ha^{-1} application of benzobicyclon, with the exception of *S. pygmaea* which was controlled 70%. Control of 90 to 100% was observed on all weed species treated with 600 g ha^{-1} applied PRE. At the one-leaf timing barnyardgrass, *S. juncoides, M. vaginalis*, *L. dubia*, and *C. serotinus* were controlled 85 to 100% when treated with benzobicyclon applied at any rate evaluated; however, *S. pygmaeae* was controlled 55, 70, and 80% when treated with 200, 300 and 600 g ha^{-1} of benzobicylcon, respectively, at the one-leaf stage. *S. juncoides* and *M. vaginalis* control was 90 to 99% from any rate of benzobicyclon applied at the two-leaf stage. Control of *S. juncoides*, barnyardgrass, *C. serotinus*, and *S. pygmaeae* did not exceed 90% when treated with benzobicyclon applied at the two-leaf stage at 200, 300, and 600 g ha^{-1}. This research demonstrates benzobicyclon activity on a diverse spectrum of weed species but suggests that the most consistent control results from early application on small actively growing weeds. Young et al. (2015) observed complete control of ducksalad, California arrowhead, and ALS-resistant smallflower umbrella sedge (*Cyperus difformis* L.) when benzobicyclon was mixed with halosulfuron.

Komatsubara et al. (2009) evaluated the toxicity of benzobicyclon across a wide variety of non-target organisms and observed little or no toxicity in birds, insects, algae, or soil microorganisms. A favorable ecotoxicological profile is desired for herbicides applied near Louisiana crawfish production systems to prevent losses from non-target movement and subsequent toxicity. Approximately 3% benzobicyclon was absorbed into rice plants and none was detected in grain, indicating this herbicide exhibits desirable characteristics regarding pesticide residue in the marketable commodity.

Sekino et al. (2008) applied benzobicyclon directly into flood water and observed weed control, indicating that this herbicide is active in water. Further evaluation is needed on benzobicyclon activity in mid-south rice cropping systems, particularly in Louisiana where water-seeded rice plantings are common. Past benzobicyclon research indicates enhanced weed control when applied early to small actively growing weeds (Sekino et al. 2008).

Ducksalad germinates when the soil is flooded and becomes a competitive problem earlier in a water-seeded system compared with drill-seeded rice (Smith 1968). Marler (1969) determined that ducksalad seeds require nearly full anaerobic conditions for germination and germination is inhibited when oxygen concentration is above 1%. Ducksalad competition with rice seedlings is a common problem early in the growing season in Louisiana water-seeded rice (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). Smith (1965) reported that propanil is ineffective for the control of ducksalad, and control with herbicides requiring foliar contact can be difficult and costly as flood water must be lowered to expose submersed ducksalad foliage (Sankula et al. 1997; Webster 2014). Braverman (1995) reported postflood ducksalad control with bensulfuron coated fertilizer granules; however, coating fertilizer with herbicides can be costly and time consuming. Louisiana rice producers utilizing water-seeded systems could benefit from a herbicide with these unique characteristics when applied to rice fields under flooded conditions.

Yellow nutsedge can tolerate high soil moisture (Bendixen and Nandihalli 1987) and is a common weed pest in Louisiana rice production (Webster 2014). Tubers are produced on rhizomes and contain several buds or tubers, and these tubers are the main mode of dispersal and reproduction of this species (Stoller and Sweet 1987). Taylorson (1967) reported yellow nutsedge tubers are dormant in the late summer and fall, and sprouted vegetative tissue the following spring. Seed production is typically very low and seeds that are produced have low germination and poor seedling vigor (Thullen and Keeley 1979). Yellow nutsedge can reduce cotton yield 463 kg ha^{-1} after four weeks of competition (Patterson et al. 1980) and heavy infestations can reduce corn yield as much as 41% (Stoller et al. 1979). Blum at al. (2000) controlled yellow nutsedge in bermudagrass turf 100, 93 and 98% with sulfentrazone, halosulfuron or bentazon, respectively, 14 DAT. Tubers from plants treated with sulfentrazone, halosulfuron, and bentazon had a germination rate of 52, 43, and 66%, respectively. Webster et al. (2008) observed a reduction in tuber biomass following glyphosate applied at 410 g ae ha^{-1}. Bentazon and halosulfuron are labeled for use in Louisiana rice production for sedge and broadleaf control (Webster 2016). Halosulfuron resistant yellow nutsedge was confirmed in Arkansas in 2013 (Heap 2017). Increasing confirmations of ALS resistance in *Cyperus spp*. would benefit from herbicides employing an alternative mode of action in rice production, which would serve as another component to an overall resistance management program (Norsworthy et al. 2012).

The objectives of this research will focus on evaluating benzobicyclon application timing for weed control in a water-seeded system, evaluating the rate response of benzobicyclon applied at several different rates on common Louisiana rice weed species, evaluating benzobicyclon in mixture with imazethapyr and imazamox in IR rice production, and the impact of benzobicyclon application at different rates into two different flood depths on yellow nutsedge.

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Chapter 2

Benzobicyclon Application Timing in Water-Seeded Rice Production

Introduction

Both dry-seeded and water-seeded planting practices are employed in Louisiana rice production (Harrell and Saichuk 2014). Water-seeded rice accounted for approximately 35% of the planted area in Louisiana in the 2016 growing season (Harrell 2016). In water-seeded production, three different flood systems are commonly utilized. These include the delayed flood, pinpoint flood, and the continuous flood. In the delayed flood system, fields are drained following seeding for a period of 3- to 4-weeks before the permanent flood is established. A pinpoint flood system is characterized by draining for 3- to 5-days following water seeding to allow for seedling establishment before the permanent flood is established. In the continuous flood system, flood water remains on the field from the time of seeding until draining for harvest (Harrell and Saichuk 2014).

The water-seeded method of planting rice crops has been utilized for many years in south Louisiana as a means of red rice suppression early in the growing season by creating a soil environment that reduces germination of red rice (Dunand et al. 1985; Harrell and Saichuk 2014). Weed complexes are usually different in water-seeded plantings compared with dry-seeded plantings (Hill et al. 1994; Smith et al. 1973; Smith et al. 1977). Smith (1988a) described a common weed spectrum in dry-seeded production systems including barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], bearded sprangletop [*Leptochloa fascicularis* var. *panicoides* (Lam.) Grey], eclipta [*Eclipta prostrata* (L.)L.] and spreading dayflower (*Commelina diffusa* Burm. F.). Barnyardgrass and bearded sprangletop can emerge and compete in water-seeded rice production systems that utilize a temporary draining of flood water for seedling establishment. Several aquatic weeds have the ability to emerge through an established flood early in water-seeded rice production systems including ducksalad [*Heteranthera limosa* (Sw.) Willd.], purple ammannia (*Ammannia coccinea* Rottb.), and disk waterhyssop [*Bacopa rotundifolia* (Michx.) Wettst.] (Smith 1988a). Ducksalad and purple ammannia have been included in the 10 most common weeds in rice among Southern U.S. rice producing states (Webster 2011).

Rice fields in south Louisiana are often rotated with crawfish [*Procambarus clarkii* (Girard); *Procambarus zonangulus* (Hobbs & Hobbs)] aquaculture production systems. The extended period of inundation from flood irrigation in this rotational system selects for weed species that would otherwise not present a problem in rotations with lengthy periods of non-flooded soil conditions (Webster 2014). These aquatic weeds include pickerelweed (*Pontederia chordata* L.), ducksalad, creeping burhead [*Echinodorus cordifolius* (L.) Griseb.], grassy arrowhead (*Sagittaria graminea* Michx. var. *graminea*), common arrowhead (*Sagittaria latifolia* Willd.), purple ammannia, Indian toothcup [*Rotala indica* (Willd.) Koehne] and disk waterhyssop.

In the early 1990s, barnyardgrass resistance to propanil was discovered in Arkansas (Baltazar and Smith 1994; Carey et al. 1995), and barnyardgrass with multiple resistances to propanil and quinclorac, was confirmed in Arkansas in 1999 (Malik et al. 2010). Populations of barnyardgrass resistant to clomazone and imazethapyr were identified in Arkansas in 2007 and 2008, respectively (Norsworthy 2009; Wilson 2011). Barnyardgrass populations resistant to propanil, quinclorac and imazethapyr have been documented in Louisiana in 1995, 1998, and 2013, respectively (Heap 2017), and Amazon sprangletop resistant to cyhalofop-butyl and fenoxaprop-P-ethyl was confirmed in Louisiana in 2009. Rice flatsedge resistant to acetolactase synthase (ALS) (EC 4.1.3.18) inhibiting herbicides were identified in Arkansas and Mississippi in 2010 and in Louisiana in 2013. Rotating herbicide mode of action is one strategy included within an overall resistant management program (Norsworthy et al. 2012). The adoption of herbicides with a mode of action not currently labeled for use in a particular crop can enhance resistance management strategies and possibly delay the development of herbicide resistance.

Ducksalad is a troublesome early-season weed in water-seeded rice fields in south Louisiana (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). This weed germinates simultaneously with water-seeded rice and early control of this species is necessary to prevent yield loss (Smith 1968). Four weeks of ducksalad competition can reduce rice yield and season-long ducksalad competition can reduce rough rice yields by 21% (Smith 1988b). Smith (1965) reported that ducksalad control with propanil was ineffective and other herbicides would be needed to obtain control of this weed in rice production. Control with herbicides requiring contact with foliage can be difficult and costly as flood water must be lowered to expose submerged ducksalad plants (Sankula et al. 1997; Webster 2014).

Benzobicyclon is a 4-hydroxyphenylpyruvate dioxygenase (EC 1.13.11.27) inhibiting herbicide herbicide that has been labeled for use in Japan since 2001 (Komatsubara et al. 2009). Past research has indicated benzobicyclon is effective on susceptible weed species when applied at preemergence (PRE) or post-emergence following the establishment of the flood (POSTFLOOD) (Sekino et al. 2008). Common weeds occurring in Japan rice fields were treated with 200, 300, and 600 g ai ha^{-1} at PRE, one-leaf and two-leaf application timings. Benzobicyclon applied PRE at 200 g ha^{-1} controlled *Monochoria vaginalis* [(Burm. f.) C. Presl. ex Kunth], *Schoenoplectus juncoides* [(Roxb.) Palla], barnyardgrass, *Cyperus serotinus* (Rott.), and *Lindernia dubia* [(L.) Pennell var. dubia] 90% or greater; however, to obtain this level of control for *S. pygmaea* benzobiyclon applied at 600 g ha^{-1} was needed. Benzobicyclon applied at 200 to 600 g ha^{-1} on one-leaf weeds controlled barnyardgrass, *S. juncoides*, *M. vaginalis*, *L. dubia*, and *C. serotinus* 85 to 100%. Benzobicyclon applied on two-leaf weeds at 200 g ha^{-1} controlled *S. juncoides* and *M. vaginalis* 90 to 99%; however, benzobicyclon did not control two-leaf barnyardgrass, *L. dubia* or *C. serotinus* greater than 90%. While benzobicyclon has activity on a wide weed spectrum, weeds must be small and actively growing for acceptable control of the species listed in this study.

Benzobicyclon must undergo a hydrolysis reaction in the presence of water to render the active herbicide, benzobicyclon-hydrolysate (Komatsubara et al. 2009), and this conversion is impacted by pH, temperature, and dissolved organic carbon in water (Williams and Tjeerdma 2016). Benzobicyclon applied directly to flood water can be taken up by plants mainly through root and shoot tissue (Sekino et al. 2008). This herbicide also controlled susceptible species 8 weeks after treatment, indicating this product has a long residual profile under flooded conditions. In the laboratory approximately 3% of the applied benzobicyclon was absorbed into rice plants and none of the herbicide translocated into rice grain (Komatsubara et al. 2009).

Komatsubara et al. (2009) also evaluated the toxicity of benzobicyclon across a wide variety of non-target organisms and observed little or no toxicity to birds, insects, algae, or soil microorganisms. A favorable ecotoxicological profile is desired for herbicides applied near Louisiana crawfish aquaculture production systems to prevent losses from non-target movement and subsequent toxicity. Because of the unique water activity properties of benzobicyclon and a favorable ecotoxicological profile, this product could be a useful herbicide in Louisiana water-seeded production for the control of troublesome early-season weeds including ducksalad. The objective of this research was to evaluate benzobicyclon application timing effects on weed control in water-seeded rice, utilizing a pinpoint flood.

Materials and Methods

A field study was conducted in the 2013, 2014, and 2015 growing seasons at the LSU AgCenter H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana. Soil at the study location was a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.3 and 1.3% organic matter. Seedbed preparation included a fall and spring disking followed by two perpendicular passes with a two-way bed conditioner employing S-tine harrows, set at a 4-cm depth, and rolling baskets. Following seedbed preparation, 1.5 by 5.2 m^2 plots were established and 91-cm diameter by 30-cm tall galvanized metal rings were placed at random near the center of each plot and pressed firmly into the soil approximately 5-cm to seal the area contained inside the ring from the rest of the plot area. Sekino et al. (2008) observed increased activity of benzobicyclon when applied directly to flood water, and the galvanized metal ring was used to allow for herbicide containment without the need for individually-leveed plots. Weed evaluations were only taken within the ring; however the entire plot area, 1.5 by 5.2 m^2, was treated.

Water management strategies in water-seeded rice plantings can vary, but the specific water management selected for this field study utilized a pinpoint flooding system. At planting, a seeding flood 5-cm in depth was introduced onto the field and pre-germinated ‘CL-111’ rice seed was hand-broadcasted onto the plot area at a rate of 112 kg ha^{-1}. Approximately 48 h after seeding, the flood was drained from the field to allow rice seedling establishment for approximately 5- to 7-days. When rice seedlings had produced a radical anchored into the soil with a coleoptile 2.5-cm in length, rice was considered at the pegging growth stage. At 24 h following determination of the pegging growth stage a pinpoint flood was introduced onto the study area at a depth not completely submerging the tip of the coleoptile and raised as rice plants elongated until a final flood depth of 10-cm was achieved. Fertility and other pest management practices were based on recommendations from the LSU AgCenter Rice Production Guidelines (Harrell and Saichuk 2014).

Benzobicyclon (Gowan Company, Yuma, Arizona) was applied at preplant onto dry soil (SURFACE), into the seeding flood 24 h after seeding (SEED), 24 h after the draining of the seeding flood (POSTSEED), on pegging rice 24 h prior to the pinpoint flood establishment (PEG), 24 h following the establishment of the pinpoint flood (PIN), on three- to four-leaf rice or mid-postemergence (MPOST), and one- to two-tiller rice or late postemergence (LPOST), utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} of spray solution at 190 kPa.

Experimental design for this field study was a randomized complete block design replicated four times. Herbicide treatments consisted of benzobicyclon applied at a rate of 246 g ha^{-1} at the seven different, previously mentioned application timings. All herbicide treatments applied at the PEG timing and later included 1% v v^{-1} crop oil concentrate (COC)(Agri-Dex®, Helena Chemical Company, Collierville, TN). Weeds had not germinated in the research area at the SURFACE, SEED, and POSTSEED application timings and weed sizes at later application timings are listed in Table 2.1.

Visual weed control ratings were recorded at 21, 35, and 49 DAT. Visual weed control ratings were assigned on a scale of 0 to 100%, where 0 = no injury and 100 = complete plant death. Rice plant heights were recorded immediately prior to harvest by randomly selecting four rice plants within each ring and measuring from the soil to the tip of the extended panicle. The front and back of each plot was trimmed to achieve a total plot length of 3.6 m immediately prior to harvest. The center 0.75 by 3.6 m area of each plot was harvested on July 29 in 2013, August 11 in 2014, and July 28 in 2015 with a Mitsubishi® VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2-chome, Chiyoda-ky, Tokyo, Japan) rice harvester. Rough rice was adjusted to 12% moisture for yield determination.

Table 2.1. Weed size and growth stage at time of benzobicyclon application in 2013, 2014, and 2015.

Application timing[a]	Weed growth stage and size					
	Barnyardgrass		Ducksalad		Yellow nutsedge	
	Stage[b]	– cm –	Stage[b]	– cm –	Stage	– cm –
PEG	1 lf	3-5	—	—	3-6 lf	5-10
PIN	1-2 lf	5-8	cot	0.5-1	3-9 lf	10-20
MPOST	4-5 lf	7-15	cot-1 lf	15-30	6-12 lf	15-25
LPOST	5 lf-1 till	15-30	3-4 lf	15-30	9-12 lf	25-45

[a]Application timings: PEG applied on pegging rice, PIN applied 24 h following the establishment of the permanent pinpoint flood, MPOST applied on three- to four-leaf rice, LPOST applied on one- to two-tiller rice.
[b]Abbreviations: lf, leaf; till, tiller; cot, cotyledon.

Data were arranged as repeated measures and subjected to the mix procedure of SAS (release 9.4, SAS Institute, Cary, NC). Location, years, replication (nested within year) and all interactions including any of these effects were considered random effects. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al. 1989; Hager et al. 2003). Application timing of benzobicyclon and rating date was considered fixed effects. Type III statistics were used to test all possible interactions of these fixed effects. Tukey’s test was used to separate means at the 5% probability level ($p \leq 0.05$).

Results and Discussion

A herbicide application timing interaction occurred for the control of barnyardgrass (Table 2.2); therefore, data were averaged over evaluation timing. Benzobicyclon applied at the PEG and PIN timing controlled barnyardgrass 97 and 94%, respectively, and this control was higher than

Table 2.2. Control of barnyardgrass when treated with benzobicyclon at 246 g ha^{-1} at different application timings, averaged across evaluation timings.[ab]

Application Timing[d]	Barnyardgrass control[c]
	%
SURFACE	64 b
SEED	70 ab
POSTSEED	82 ab
PEG	97 a
PIN	94 a
MPOST	72 ab
LPOST	61 b

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.

[b]Field trials conducted in 2013, 2014 and 2015.

[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

[d]Application Timings: SURFACE applied preplant on dry soil; SEED applied into the seeding flood; POSTSEED applied 24 h following the draining of the seeding flood; PEG applied on pegging rice; PIN applied 24 h following pinpoint flood establishment; MPOST applied on three- to four-leaf rice; LPOST applied on one- to two-tiller rice.

barnyardgrass treated at the SURFACE and LPOST timings, which controlled barnyardgrass 64 and 61%, respectively. At the SURFACE application timing benzobicyclon was applied on dry soil before the seeding flood was established, which may explain the reduced barnyardgrass control since this herbicide must undergo a conversion hydrolysis reaction from benzobicyclon to benzobicyclon-hydrolysate (Komatsubara et al. 2009). Barnyardgrass size was large at the LPOST timing and may explain the reduced control (Tabel 2.1). Sekino et al. (2008) observed barnyardgrass control from benzobicyclon applied PRE and on one-leaf plants, but did not observe similar control when applied to two-leaf barnyardgrass. Benzobicyclon applied at the SEED, POSTSEED, and MPOST timings controlled barnyardgrass similar to barnyardgrass treated at the PEG and PIN application timings (Table 2.2).

An evaluation timing interaction occurred for the control of barnyardgrass (Table 2.3); therefore, data were averaged over application timing. At 21 DAT, barnyardgrass control was 72%; however, barnyardgrass control at the time of the final evaluation timing, 49 DAT, increased to 82%. Sekino et al. (2008) observed long residual control from benzobicyclon applications, and at the last evaluation, 49 DAT, full rice canopy closure in concert with the long residual profile of benzobicyclon may explain why banryardgrass control increased at later evaluations.

Table 2.3. Control of barnyardgrass at different evaluation timings following treatment with benzobicyclon at 246 g ha^{-1}, averaged over application timings.[ab]

Evaluation timing	Barnyardgrass control[c]
—— DAT ——	—————— % ——————
21	72 b
35	79 a
49	82 a

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test.
[b]Field trials conducted in 2013, 2014 and 2015.
[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

A herbicide application timing by evaluation timing interaction occurred for the control of yellow nutsedge (Table 2.4). At 21 DAT, yellow nutsedge treated with benzobicyclon at the SURFACE, MPOST, and LPOST application timings was controlled 53, 33, and 21%, respectively. Increased yellow nutsedge control of 95% was observed at 21 DAT when benzobicyclon was applied at the PEG application timing. At 35 and 49 DAT, yellow nutsedge

Table 2.4. Control of yellow nutsedge when treated with benzobicyclon at 246 g ha^{-1} at different application timings across three evaluation timings.[a,b]

Application timing[c]	Yellow nutsedge control[d]		
	21 DAT	35 DAT	49 DAT
		%	
SURFACE	53 d-g	56 c-g	64 b-e
SEED	61 b-e	71 a-e	78 a-d
POSTSEED	65 b-e	80 a-d	90 abc
PEG	95 ab	98 a	97 a
PIN	63 b-f	92 abc	96 ab
MPOST	33 ej	78 a-d	79 a-d
LPOST	21 g	59 c-f	66 b-e

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test within and across columns and rows.
[b]Field trials conducted in 2013, 2014 and 2015.
[c]Application Timings: SURFACE applied preplant on dry soil; SEED applied into the seeding flood; POSTSEED applied 24 h following the draining of the seeding flood; PEG applied on pegging rice; PIN applied 24 h following pinpoint flood establishment; MPOST applied on three- to four-leaf rice; LPOST applied on one- to two-tiller rice.
[d]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

control from benzobicyclon application at the PEG timing was 98 and 97%, respectively. This level of yellow nutsedge control from the PEG timing was increased over control observed from SURFACE and LPOST applications at 35 and 49 DAT. Yellow nutsedge plants treated with benzobicyclon at the LPOST application timing were larger (Table 2.1) than *C. serotinus* plants controlled with benzobicyclon applied at PRE and one-leaf application timings (Sekino et al. 2008), which may explain the reduced control on yellow nutsedge in this study. The SURFACE application was applied to dry soil and the lack of water for the necessary conversion reaction to occur (Komatsubara et al. 2009) may explain reduced yellow nutsedge control from this application timing.

A herbicide application timing by evaluation timing interaction occurred for ducksalad control (Table 2.5). At 21 DAT, ducksalad control was 96% from benzobicyclon applied at the PIN timing, and was increased compared to control observed from the SURFACE, SEED, POSTSEED and PEG application timing which was 72, 67, 61, and 66%, respectively. By 49 DAT, ducksalad control from benzobicyclon application at the SURFACE and PIN timing was 93 and 95%, respectively, and was higher when compared with ducksalad control from the PEG application timing with 69%. Ducksalad control was greater than 90% at all evaluation timings from benzobicyclon applied at the PIN timing, indicating early application into the permanent flood is needed to achieve the most consistent ducksalad control. Ducksalad was smaller at this application timing compared with later timings (Table 2.1), and small weed size in concert with application into the permanent flood may explain ducksalad control greater than 90% at all evaluation timings.

An application timing interaction occurred for rough rice yield (Table 2.6). Rice treated with benzobicyclon at the SURFACE application timing yielded higher rough rice grain, 8450 g ha^{-1}, when compared with the nontreated rice with a yield of 7270 ka ha^{-1} (Table 2.6). Grain yield from rice treated with benzobicyclon at any application timing did not differ. Rice treated with benzobiyclon at any application timing yielded 106 to 116% of the nontreated rice. No differences in plot height occurred across all benzobicyclon application timings and the nontreated (Data not shown).

The scope of this study was to evaluate benzobicyclon in a simulated water-seeded production system specifically utilizing a pinpoint flood. Often in commercial water-seeded fields in Louisiana, ducksalad can become a significant early-season pest (Eric Webster, LSU AgCenter Extension Weed

Table 2.5. Control of ducksalad when treated with benzobicyclon at 246 g ha^{-1} at different application timings across three evaluation timings.[ab]

Application timing[c]	Ducksalad control[d]		
	21 DAT	35 DAT	49 DAT
		%	
SURFACE	72 cd	78 bcd	93 ab
SEED	67 cd	72 cd	89 abc
POSTSEED	61 cd	66 cd	75 bcd
PEG	66 cd	66 cd	69 cd
PIN	96 a	95 ab	95 ab
MPOST	81 abc	83 abc	83 abc
LPOST	75 bcd	80 abc	81 abc

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test within and across colums and rows.
[b]Field trials conducted in 2013, 2014 and 2015.
[d]Application Timings: SURFACE applied preplant on dry soil; SEED applied into the seeding flood; POSTSEED applied 24 h following the draining of the seeding flood; PEG applied on pegging rice; PIN applied 24 h following pinpoint flood establishment; MPOST applied on three- to four-leaf rice; LPOST applied on one- to two-tiller rice.
[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

Table 2.6. Rough rice yield of rice treated with benzobicyclon applied at 246 g ha^{-1} at different application timings.[ab]

Application timing[c]	Rough rice yield	
	— kg/ha —	— % of nontreated —
Nontreated	7270 b	—
SURFACE	8450 a	116
SEED	8200 ab	113

Table 2.6 continued.

Table 2.6 continued.

Application timing[c]	Rough rice yield	
	— kg/ha —	— % of nontreated —
POSTSEED	8400 ab	116
PEG	7710 ab	106
PIN	8290 ab	114
MPOST	7990 ab	110
LPOST	8360 ab	115

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.

[b]Field trials conducted in 2013, 2014 and 2015

[c]Application Timings: SURFACE applied preplant on dry soil; SEED applied into the seeding flood; POSTSEED applied 24 h following the draining of the seeding flood; PEG applied on pegging rice; PIN applied 24 h following pinpoint flood establishment; MPOST applied on three- to four-leaf rice; LPOST applied on one- to two-tiller rice.

Scientist, personal communication) and competition with rice can impact yield and effect quality (Smith 1968). Other studies conducted at LSU have demonstrated the efficacy of benzobicyclon on a pure stand of ducksalad where no rice was present for competition (McKnight et al. 2016). This trial demonstrates that excellent ducksalad activity can be obtained from benzobicyclon, and application made immediately after the permanent flood establishment provides consistent ducksalad control greater than 90%. Braverman (1995) observed similar control of ducksalad with fertilizer granules coated with bensulfuron at 111 g ha^{-1}. Coating fertilizer granules with herbicides require extra time and costs, and effective ducksalad control with benzobicyclon can be achieved by applying the herbicide in a liquid spray solution. Braverman and Jordan (1996) observed poor ducksalad control from POSTFLOOD applications of bispyribac-sodium. Herbicides requiring foliar contact with ducksalad to be active must be applied after the flood level is adjusted to expose ducksalad foliage (Sankula et al 1997; Webster 2014).

Lowering and re-establishing the flood can also incur more money and time expense to producers, in addition to the cost of herbicide application. Because of the unique activity of benzobicyclon in flood water (Komatsubara et al 2009; Williams and Tjeerdma 2016), flood water manipulation is not necessary for ducksalad activity.

Populations of barnyardgrass have been identified in recent years with resistance to single and multiple modes of action currently utilized in rice production (Baltazar and Smith 1994; Carey et al. 1995; Heap 2017; Malik et al. 2010; Norsworthy 2009; Wilson 2011). Rotating herbicide mode of action is a component to an overall resistance management program (Norsworthy et al. 2012). Benzobicyclon is an HPPD inhibiting herbicide, and this new mode of action in rice production could help manage barnyardgrass populations infesting rice fields that are resistant to other modes of action when applied to barnyardgrass when it is small, one- to three-leaf, and actively growing.

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Chapter 3

Benzobicyclon Applied at Different Rates on Common Louisiana Rice Weeds

Introduction

Weeds are troublesome pests in U.S. rice production and compete with rice for nutrients, sunlight and water resources, and through interspecific competition rice quality can be negatively impacted (Smith 1968; Smith 1988). Monocot weed species common in Louisiana rice production include spreading dayflower (*Commelina diffusa* Burm. F.), Nealley's sprangletop (*Leptochloa nealleyi* Vasey), Amazon sprangletop [*Leptochloa panicoides* (J. Presl) Hitchc.], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], junglerice (*Echinochloa colona* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] and red rice (*Oryza sativa* L.) (Bergeron et al. 2015a; Bergeron et al. 2015b; Webster 2011). Several perennial grasses including creeping rivergrass [*Echinochloa polystachya* (Knuth) Hitch.], water paspalum (*Paspalum hydrophilum* Henr.), brook crowngrass (*Paspalum acuminatum* Raddi) and knotgrass (*Paspalum distichum* L.) can also be troublesome in south Louisiana rice fields (Bottoms et al. 2011; Griffin et al. 2008; Webster 2007). Broadleaf weeds common in Louisiana rice production systems include Texasweed [*Caperonia palustris* (L.) St. Hil.], alligatorweed [*Alternanthera philoxeroides* (Mart.) Grisb.], Indian jointvetch (*Aeschynomene indica* L.) and hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] (Webster 2014). Plants of the *Cyperaceae* family including yellow nutsedge (*Cyperus esculentus L.*) and rice flatsedge (*Cyperus iria* L.) are found in nearly every rice field in Louisiana.

Rice crops are often rotated with crawfish production in Louisiana and this rotation can involve continuous flood conditions 11 months or longer. Aquatic weeds including ducksalad [*Heteranthera limosa* (Sw.) Willd.], grassy arrowhead (*Sagittaria graminea* Michx. var. *graminea*), common arrowhead (*Sagittaria latifolia* Willd.), creeping burhead [*Echinodorus cordifolius* (L.)

Griseb.], and pickerelweed (*Pontederia chordata* L.) can become troublesome weeds following crawfish production especially in rice production the next year (Webster 2014).

The level of competition of common rice weeds varies between species and duration of competition. Red rice, *Echinochloa spp*., bearded sprangletop and broadleaf signalgrass reduced rice yield 82, 70, 36, 35 and 32%, respectively, following season-long competition (Diarra et al. 1985; McGregor 1986; Smith 1968; 1974; 1983). Season-long ducksalad, hemp sesbania, spreading dayflower and *Aeschynomene* spp. reduced rice yield 21, 19, 18 and 17%, respectively (Smith 1968; 1984). Weeds also reduce rice quality and interfere or impact harvesting efficiency. The presence of *Ipomoea* and hemp sesbania seeds in harvested rice grain reduces grade and has a negative impact on the value of the harvested crop (Smith 1988; Smith et al. 1977). Purple ammannia (*Ammannia coccinea* Rottb.) seed pods in rice grain can lower the value and increase the cost of drying harvested grain (Smith et al. 1977).

Smith (1988) described a difference in weed complexes depending on planting practices and water management of a rice crop. Common dry-seeded weeds include barnyardgrass, sprangletop spp., eclipta [*Eclipta prostrata* (L.)L.] and spreading dayflower. Barnyardgrass and sprangletop spp. can emerge and be competitive with rice in water-seeded systems where flood water is temporarily drained to allow for rice seedling establishment. Aquatic weeds including purple ammannia and ducksalad can emerge through a permanent flood established early in water-seeded plantings.

Weed resistance to herbicides has become a problem in rice production throughout the last two decades. In the early 1990s, barnyardgrass resistance to propanil was discovered in Arkansas (Baltazar and Smith 1994; Carey et al. 1995), and barnyardgrass with multiple resistances to propanil and quinclorac was confirmed in Arkansas in 1999 (Malik et al. 2010). Populations of barnyardgrass resistant to clomazone and imazethapyr were identified in Arkansas in 2007 and 2008, respectively (Norsworthy 2009; Wilson 2011). Barnyardgrass populations resistant to propanil, quinclorac and imazethapyr have been documented in Louisiana in 1995, 1998, and 2013, respectively (Heap 2017). Amazon sprangletop resistant to cyhalofop-butyl and fenoxaprop-P-ethyl was confirmed in Louisiana in 2009. Rice flatsedge resistant to acetolactase synthase inhibiting herbicides was confirmed in Arkansas and Mississippi in 2010 and in Louisiana in 2013. One strategy included in an overall resistance management program is rotating herbicide mode of action (Norsworthy et al. 2012). The adoption of herbicides with a mode of action not currently labeled for use in a particular crop can enhance resistance management strategies and possibly delay the development of herbicide resistance.

Benzobicyclon is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) (EC 1.13.11.27) inhibiting herbicide that has been labeled for use in Japan since 2001 (Komatsubara et al. 2009). Sekino et al. (2008) reported preemergence (PRE) and postemergence (POST) activity on susceptible weeds at 200 and 300 g ai ha^{-1} rates. Activity of benzobicyclon is dependent on the uptake of the herbicide through root and shoot tissue, and this occurs more readily under flooded conditions compared with dry soil application.

Komatsubara et al. (2009) concluded that benzobicyclon must undergo a hydrolysis reaction in the presence of water to render the active herbicide, benzobicyclon-hydrolysate. Williams and Tjeerdema (2016) determined that water pH, temperature, and the presence of dissolved organic carbon effects conversion of benzobicyclon to benzobicyclon-hydrolysate and the half-life of benzobicyclon in basic conditions was 5 to 28 h. Control of *Schoenoplectus juncoides* [(Roxb.) Palla] was observed 8 weeks after treatment, indicating benzobicyclon provides residual control. Weed species common to rice production in Japan that are susceptible to benzobicyclon at early application timings include barnyardgrass, *Monochoria vaginalis* [(Burm. f.)

C. Presl. ex Kunth], *Schoenoplectus juncoides, Cyperus serotinus* (Rott.), *Sagittaria pygmaea* (Miq.), *Lindernia dubia* [(L.) Pennell var. dubia] (Sekino et al. 2008). *Cyperus, Sagittaria,* and *Schoenoplectus*, as well as barnyardgrass and *Lindernia dubia*, occur as weeds in Louisiana rice production. The focus of this field trial was to evaluate benzobicyclon applied at different rates on common Louisiana rice weeds at multiple locations and years.

Materials and Methods

Field studies were conducted at the LSU AgCenter H. Rouse Caffey Rice Research Station near Crowley, Louisiana in 2013, 2014, 2015, and 2016 on a Crowley silt loam soil (fine smectic, thermic Typic Albaqualfs) with a pH of 6.3 and 1.3% organic matter, and on a Midland silty clay loam (fine, smectitic, thermic Chromic Vertic Epiaqualf) with 1.2% organic matter and pH 6.1 in 2015 and 2016. This trial was also conducted at the LSU AgCenter Northeast Research Station (NERS) near St. Joseph, Louisiana on a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquert) with a pH 6.1 and 2.1% organic matter in 2015. Seedbed preparation included a fall and spring disking followed by two perpendicular passes with a two-way bed conditioner employing S-tine harrows, set at a 10-cm depth, and rolling baskets. Following seedbed preparation, 1.5 by 5.2 m^2 plots were established and 91-cm diameter by 30-cm tall galvanized metal rings were placed at random near the center of each plot and pressed firmly into the soil at a depth of 5-cm to seal the area contained inside the ring from the rest of the plot area. Sekino et al. (2008) observed activity of benzobicyclon when applied directly to flood water, and the galvanized metal ring was used to allow for herbicide containment without the need for individually-leveed plots. Weed evaluations were only taken within the ring; however, the entire plot area, 1.5 by 5.2 m^2, is treated.

Water management for this field trial mimicked a water-seeded production system; however, no rice was planted in the plot area to eliminate competition between rice plants and a natural weed infestation. Lack of competition from rice allows the full effect of the herbicide treatment to be evaluated without interference from shading and resource competition. Once the permanent flood was established and ducksalad had reached the first elongated leaf growth-stage, benzobicyclon treatments were applied postemergence following the flood (POSTFLOOD). The rates evaluated were 0, 31, 62, 123, 185, 246, 493, 739, 986, and 1232 g ha^{-1}. The target field rate of benzobicyclon is 246 g ha^{-1}. All treatments included 1% v v^{-1} crop-oil-concentrate (COC) (Agri-Dex®, Helena Chemical Company, Collierville, TN). Applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140-L ha^{-1} of spray solution at 190 kPa. The entire 1.5 by 5.2 m^2 plot area was treated with herbicide. Fertility and other pest management practices were based on recommendations from the LSU AgCenter Rice Production Guidelines (Harrell and Saichuk 2014). Experimental design for this field study was a randomized complete block design replicated four times.

At the time of herbicide application, ducksalad, barnyardgrass and yellow nutsedge had emerged through the flood and were present in each individual ring. Ducksalad was at the first elongated leaf stage, or 3- to 8-cm, barnyardgrass was at the one- to three-tiller stage, or 20- to 25-cm, and yellow nutsedge plants were at the nine- to 12-leaf stage, or 20- to 30-cm. Purple ammannia was present in the study area, but submerged below the flood water and was at the two- to four-leaf stage or, 1- to 2-cm at the time of herbicide treatment. Visual weed control evaluations were only recorded at 7, 21, 35, and 49 DAT inside the confined galvanized ring confined. Visual weed control evaluations were assigned on a scale of 0 to 100%, where 0 = no injury and 100 = complete plant death. At the conclusion of the study all weed biomass above the soil surface from each treatment containment ring was hand-harvested and separated by species for fresh weight determination.

Data were arranged as repeated measures and subjected to the mix procedure of SAS (release 9.4, SAS Institute, Cary, NC). Location, years, replication (nested within year) and all interactions including any of these effects were considered random effects. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al. 1989; Hager et al. 2003). Application rate of benzobicyclon and evaluation date were considered fixed effects. Type III statistics were used to test all possible interactions of these fixed effects. Tukey’s test was used to separate means at the 5% probability level ($p \leq 0.05$).

Results and Discussion

A herbicide treatment interaction across all evaluation timings was observed on barnyardgrass, yellow nutsedge, ducksalad, and false pimpernel (Table 3.1). Barnyardgrass and yellow nutsedge treated with any rate of benzobicyclon did not exceed 50% control. Benzobicyclon controlled ducksalad 58% with a 123 g ha^{-1} application rate, indicating this weed is more susceptible to benzobicyclon treatment than barnyardgrass and yellow nutsedge. Ducksalad treated with benzobicyclon at 493 g ha^{-1} was controlled 83% with no difference observed when applied at rates of 493 to 1232 g ha^{1}. Similar ducksalad control was observed by Braverman (1995) with bensulfuron-coated fertilizer granules applied at 111 g ai ha^{-1}, and this research indicates bensulfuron and benzobicyclon applied POSTFLOOD is more active than bispyribac-sodium for ducksalad control under flooded conditions (Braverman and Jordan 1997). False pimpernel control was similar to barnyardgrass and yellow nutsedge, never exceeding 50% control from any rate of benzobicyclon applied. Control false pimpernel was 24, 49 and 43% with 739, 986 and 1232 g ha^{-1} benzobicyclon, respectively.

Table 3.1. Control of barnyardgrass, yellow nutsedge, ducksalad and false pimpernel treated with benzobicyclon at different rates, averaged across evaluation timings.[a,b]

Benzobicyclon	Control[c]			
	Barnyardgrass	Yellow nutsedge	Ducksalad	False pimpernel
g ai ha^{-1}	%			
0	0 h	0 f	0 g	0 b
31	2 gh	1 f	12 fg	3 b
62	5 fgh	4 ef	33 e	4 b
123	12 efg	7 e	58 d	8 b
185	15 def	14 d	69 cd	8 b
246	17 de	18 d	79 bc	11 b
493	25 cd	29 c	83 ab	9 b
739	35 bc	36 b	89 ab	24 ab
986	44 ab	45 a	93 a	49 a
1232	50 a	50 a	93 a	43 a

[a]Means followed by the same letter within each column do not significantly differ at P=0.05 using Tukey's test.
[b]Field trials conducted in 2013, 2014, 2015 and 2016.
[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

An evaluation timing interaction was observed on barnyardgrass, yellow nutsedge, ducksalad and false pimpernel; therefore, data were averaged over benzobicyclon rate (Table 3.2). Barnyardgrass control was 27% across all herbicide rates 14 DAT, but decreased to 15 and 19% at 28 and 42 DAT, respectively, and this further indicates that benzobicyclon has limited activity on barnyardgrass in the tillering stage of growth. Yellow nutsedge control was similar to barnyardgrass indicating a decrease in control as DAT increased; however, ducksalad treated with any rate of benzobicyclon was controlled 56% at 14 DAT and control of ducksalad increased to 64% at 42 DAT

Table 3.2. Visual control of barnyardgrass, yellow nutsedge, ducksalad and false pimpernel treated with benzobicyclon, averaged across herbicide rate.[abc]

Evaluation Timing	Control[d]			
	Barnyardgrass	Yellow nutsedge	Ducksalad	False pimpernel
– DAT[e] –	%			
14	27 a	22 a	56 b	—
28	15 c	21 a	63 a	12 b
42	19 b	18 b	64 a	21 a

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test.
[b]Field trials conducted in 2013, 2014, 2015, and 2016.
[c]Benzobicyclon rates applied were 31, 62, 123, 185, 246, 493, 739, 986, and 1232 g ha^{-1}
[d]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.
[e]Abbreviation: DAT, days after treatment.

indicating control continued to increase over time, averaged across rate. False pimpernel control was 12% at 28 DAT and increased to 21% at 42 DAT. False pimpernel can often be a late emerging weed species in Louisiana rice production (Eric Webster, Extension Weed Scientist, LSU AgCenter, personal communication). The later emergence of this species may explain why false pimpernel was not observed in the plot prior to 28 DAT.

A benzobicyclon rate by evaluation timing interaction was observed for purple ammannia and Indian toothcup control (Table 3.3). At 14 DAT, purple ammannia treated with benzobicyclon did not exceed 55% control regardless of the rate of benzobicyclon applied. This level of purple ammania control is similar to the control observed with propanil (Smith 1965). At 28 and 42 DAT, purple ammannia control was 78 and 79%, respectively, when treated with benzobicyclon at 1232 g ha^{-1}; however, this level of control did not differ in control of purple ammannia when treated with 185 to 986 g ha^{-1}. This level of

Table 3.3. Control of purple ammannia and Indian toothcup treated with different rates of benzobicyclon, at different evaluation timings.[ab]

	Control[c]				
	Purple ammannia			Indian toothcup	
Benzobicyclon	14 DAT	28 DAT	42 DAT	28 DAT	42 DAT
g ai ha^{-1}	%				
0	0 gh	3 gh	4 gh	0 d	0 d
31	2 gh	1 h	1 h	0 d	0 d
62	5 fgh	14 e-h	10 e-h	13 cd	26 cd
123	14 e-h	28 d-h	37 c-f	58 bc	58 bc
185	11 e-h	50 a-d	58 a-d	54 bc	66 bc
246	14 e-h	56 a-d	61 abc	77 ab	81 ab
493	25 d-h	67 abc	67 abc	99 a	99 a
739	36 c-g	70 ab	71 ab	99 a	99 a
986	43 b-e	76 a	80 a	99 a	99 a
1232	55 a-d	78 a	79 a	99 a	99 a

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Field trials conducted in 2013, 2014, 2015 and 2016.
[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

control indicates the target rate of benzobicyclon, 246 g ha^{-1}, provides the same level of control of purple ammannia at 1232 g ha^{-1}.

Indian toothcup, like false pimpernel, is also a later emerging weed species in Louisiana rice production (Eric Webster, Extension Weed Scientist, LSU AgCenter). This species was not present at the time of treatment or the first visual evaluation, 14 DAT. At 28 and 42 DAT, Indian toothcup treated with 493 to 1232 g ha^{-1} benzobicyclon resulted in 99% control. This level of control did not differ from the control of Indian toothcup, 77 and 81%, with the target rate of benzobicyclon, 246 g ha^{-1}; therefore, the need for a higher rate of benzobicyclon to control this weed is not needed.

A benzobicyclon rate interaction was observed on fresh weight biomass for ducksalad and Indian toothcup when the study was terminated 42 DAT (Table 3.4). No differences in fresh weight biomass were observed for barnyardgrass, yellow nutsedge, purple ammannia, or false pimpernel (Data not shown). Ducksalad treated with benzobicyclon at 31 g ha^{-1} controlled ducksalad 12% and fresh weight did not differ from the nontreated ducksalad. A rate of 62 g ha^{-1} was needed to reduce fresh weight biomass compared with the nontreated, and a similar trend was observed with the visual control evaluation (Table 3.1). Increasing the rate of benzobicyclon to the target rate of 246 g ha^{-1} followed similar trends to the visual control evaluations. Fresh weight of ducksalad treated with the target rate of benzobicyclon at 246 g ha^{-1} did not differ from the fresh weights of ducksalad treated with rates of 493 to 1232 g ha^{-1}.

Fresh weight biomass of Indian toothcup did not differ when toothcup was treated with benzobicyclon at 246 to 1232 g ha^{-1}; however, fresh weight was reduced 77 to 96% for the same rates of benzobicyclon (Table 3.4). The late emergence of Indian toothcup may have impacted the control, because it was not observed in the research area prior to the treatment and 28 DAT evaluation. However, these data indicate that the residual activity of benzobicyclon was still present at 42 DAT based on visual evaluations and fresh weight biomass at harvest.

In conclusion, this research demonstrates that benzobicyclon does have activity on common weeds infesting Louisiana rice fields. Barnyardgrass treated with benzobicyclon at 1232 g ha^{-1} did not exceed 50%. Sekino et al. (2008) reported barnyardgrass control greater than 90% when applied as a PRE. Barnyardgrass was in the one- to three-tiller growth stage when benzobicyclon treatments were applied in these field trials, which may explain the lack of

Table 3.4 Fresh weight of ducksalad and Indian toothcup treated with different rates of benzobicyclon.[ab]

Benzobicyclon	fresh weight[c] ducksalad	Indian toothcup
g ai ha^{-1}	(g)	
0	3298 a	785 a
31	2952 a	702 ab
62	1791 b	549 abc
123	1371 bc	414 abc
185	874 bcd	271 bc
246	425 cd	177 bcd
493	200 d	133 cd
739	110 d	74 cd
986	34 d	90 cd
1232	44 d	29 d

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Field trials conducted in 2013, 2014, 2015 and 2016.
[c]No differences in fresh weights of barnyardgrass, yellow nutsedge, purple ammannia, or false pimpernel, and nontreated fresh weights for these species were 204, 335, 293, and 35 g, respectively.

control. Yellow nutsedge control also did not exceed 50%, and like barnyardgrass, was large and actively growing at the time of application.

Ducksalad control was 79 to 93% when treated with benzobicyclon at 246 to 1232 g ha^{-1} (Table 3.1). Young et al. (2015) observed 99% control of ducksalad, California arrowhead, and smallflower umbrellasedge when treated with benzobicyclon at 246 g ha^{-1}. Ducksalad control from a herbicide applied POSTFLOOD that requires foliar contact can be challenging because lowering the flood may be necessary to expose ducksalad foliage (Sankula et al. 1997; Webster 2014). Braverman and Jordan (1996) observed 100% control of ducksalad with bispyribac-sodium applied LPOST before the flood was established;

however, control was less than 40% from any rate of bispyribac-sodium applied POSTFLOOD. Braverman (1995) observed excellent ducksalad control with bensulfuron-coated fertilizer granules broadcast at a rate to deliver bensulfuron applied POSTFLOOD at 111 g ha^{-1}. Benzobicyclon provides similar ducksalad control without extra time and costs associated with treating fertilizer granules with herbicide. Since benzobicyclon is active in water, lowering flood irrigation water is not necessary in order to allow sufficient herbicide contact with foliage. Ducksalad is often an early-season problem in water-seeded rice (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). Benzobicyclon will be an option for the control of early-season ducksalad infesting Louisiana water-seeded rice production systems, and the residual profile of this herbicide will be beneficial in maintaining a weed-free period until rice crops can become fully established.

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Chapter 4

Benzobicyclon Applied at Different Rates and Flood Depths on Yellow Nutsedge

Introduction

Yellow nutsedge (*Cyperus esculentus L.*) is a member of the Cyperaceae family. The leaves are erect, 3-ranked, mostly basal, and can be distinguished from purple nutsedge by leaf tips that gradually taper to a sharp point (Bryson and DeFelice 2009). The above-ground shoot of yellow nutsedge consists of a triangular fascicle of leaves that later develops into a triangular-shaped rachis. Later development includes a seed head at the apex of the rachis (Wills et al. 1980). Yellow nutsedge is capable of producing seeds; however, seed production is generally non-existent or is very low in relation to the number of inflorescences produced per plant. Seeds that are produced have low germination viability and those that do germinate lack seedling vigor required for normal development (Thullen and Keeley 1979).

Tubers, which are produced on rhizomes, contain several buds and are the main mode of dispersal and reproduction of this species (Stoller and Sweet 1987). Tuber production in yellow nutsedge is influenced by photoperiod and rhizome tissue is differentiated into tubers rather than basal buds when photoperiod is between 8 and 12 hours (Jansen 1971). As much as 28% of the total plant dry weight can be accounted for in the tubers that are produced (Williams 1982). As tubers germinate, one or more rhizomes are produced at the apical end of the tuber (Stoller et al. 1972). Tumbleson and Kommedahl (1962) concluded that 12% of tubers germinated immediately after harvest, whereas 95% germinated the following summer, indicating some inherent dormancy characteristics. Taylorson (1967) also found that yellow nutsedge tubers were dormant in late summer and early fall, and sprouted vegetative tissue the following spring. The oldest reproductive buds break dormancy first and continue in an acropetal order (Bendixen 1973). Thullen and Keeley (1975) concluded that plant longevity, or the time between germination and plant death, increased with tuber weight.

Yellow nutsedge is a problematic weed throughout the world and infests areas in tropical, subtropical, and temperate climates (Jordan-Molero and Stoller 1978). It can present problems in a variety of cropping situations and infest dryland, irrigated, or flooded systems. Cotton, corn, soybean, peanut, and rice are some of the major crops that yellow nutsedge can be particularly problematic. It can compete with crop plants directly through competition for water, nutrients, sunlight and other resources. In a removal timing study, seed cotton yield was reduced 463 kg ha^{-1} after four weeks of competition (Patterson et al. 1980). A heavy yellow nutsedge infestation can reduce corn yield as much as 41% (Stoller et al. 1979).

Yellow nutsedge is considered to be one of the ten most common weeds in Southern U.S. rice production (Webster 2011). Yellow nutsedge may also exhibit allelopathy on some crop species. Tuber residue re-applied to the soil was found to reduce soybean shoot and root production by 40 and 50%, respectively, and shoot and root tissue in corn by 46 and 45%, respectively (Drost and Doll 1980). Tames et al. (1973) identified four chemicals in yellow nutsedge tubers that are known to inhibit seedling germination; *p*-hydroxybenzoic acid, ferulic acid, vanillic acid, and *p*-coumaric acid.

There are several herbicide options available for the control of yellow nutsedge in various cropping and turfgrass systems. Blum at al. (2000) demonstrated the activity of sulfentrazone, halosulfuron, and bentazon on the control of yellow nutsedge in bermudagrass turf. A sulfentrazone, halosulfuron, or bentazon application controlled yellow nutsedge 100, 93, and 98%, respectively, 14 days after treatment (DAT). Tubers from plants treated with sulfentrazone, halosulfuron, or bentazon had germination percentages of 52, 43, and 66%, respectively. Sulfentrazone mixed with MSMA further reduced tuber germination to 6%. Glyphosate applied at 0.41 to 2.87 kg ae ha^{-1} reduces both, above-ground growth and tuber biomass (Webster et al. 2008). If a weed-free period can be maintained long enough for crop canopy closure, yellow nutsedge may have little or no impact on crop yield under these growing conditions. As shading increases, tuber, shoot and dry matter production decrease (Patterson 1982; Keeley and Thullen 1978).

Benzobicyclon is a herbicide that has been labeled for use in Japan since 2001 (Komatsubara et al. 2009). Past research has demonstrated activity of this herbicide on *Cyperus* species (Sekino et al. 2008). *Cyperus serotinus* (Rottb.) was controlled 95 and 99% when treated with benzobicyclon rates of 300 and 600 g ai ha^{-1}, respectively. Following benzobicyclon treatment at the one-leaf growth stage, *C. serotinus* was controlled 93 and 97% with 300 and 600 g ha^{-1}; however, control decreased with 300 and 600 g ha^{-1} rates applied to *C. serotinus* at the two-leaf growth stage to 75 and 85%, respectively. Benzobicyclon activity on yellow nutsedge would provide another means of controlling this troublesome weed in rice cropping systems with a mode of action not currently labeled in U.S. rice production. The objective of this research is to evaluate benzobicyclon rates and the impact of flood depth on yellow nutsedge in a glasshouse.

Materials and Methods

Glasshouse trials were conducted at the Louisiana State University campus in Baton Rouge, Louisiana in October 2013 and January 2014. Yellow nutsedge tubers (Azlin Seed Company, Greenville, Mississippi) were planted into planting trays with 50-2.5 by 2.5-cm cells containing a potting soil medium (Jiffy Mix Grower’s Choice, Jiffy Products of America, Inc., Lorain, OH) and watered regularly to induce tuber sprouting. When plants had produced three leaves and a height of 5-cm they were transplanted into 42-cm tall by 36-cm diameter, 38-L Rubbermaid® containers that were designed to hold either a 5- or 10-cm flood above a 25-cm layer of sterilized Commerce silt loam soil (fine-silty, mixed, superactive, nonacid, thermic Aeric Fluvaquent) with less than 0.1% organic matter, 80% silt, 6% sand, 14% clay, and pH 7.0. Five plants were transplanted into each container and allowed to establish 7 days before the 5- or 10-cm flood was introduced and benzobicyclon (Gowan Company, Yuma, Arizona) treatments were applied.

The study was a completely randomized design with a factorial arrangement of treatments and four replications, and each container was considered a rep. Factor A consisted of two flood depths, 5- or 10-cm. Factor B consisted of benzobicyclon herbicide applied at 0, 246, 493, 984, 1476, and 1968 g ha^{-1}. Herbicide treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140-L ha^{-1} spray solution at 190 kPa. Crop-oil-concentrate (COC) at 1% v v^{-1} (Agri-dex®, Helena Chemical Co., Collierville, TN) was added to all benzobicyclon treatments. Containers containing the yellow nutsedge plants were removed from the glasshouse and allowed to acclimate to the outside environment for 2-hours prior to and after application, and to allow thorough drying of spray solution. The glasshouse was maintained at an average diurnal regime of 30:25 ± 5 C and 60 ± 10% rH for both runs. Day length was extended to 14 h with metal halide lamps at a minimum intensity of 270 $\mu mols^2$ s^{-1} photosynthetic photon flux.

Yellow nutsedge visual injury in the form of bleaching was evaluated 14, 21, and 28 days after treatment (DAT) on a scale of 0 to 100%, where 0 = no bleaching and 100 = complete bleaching of all plant tissue. At 28 DAT, plant heights were measured from the soil to the tip of the most extended leaf. Following the final visual rating and height measurement, 28 DAT, plants were removed from soil and thoroughly rinsed to remove all soil media residue and blotted dry. The total number of tubers were counted per plant and recorded. The above ground plant tissue was separated from the below ground tissue and fresh weight was obtained for each.

Data was subjected to the mix procedure in SAS (release 9.4, SAS Institute, Cary, NC). Runs, one run in 2013 and one run in 2014, replications (nested within treatments), and all interactions containing any of these effects were considered random effects. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al. 1989; Hager et al. 2003). Flood depth, herbicide treatment and evaluation timing were considered fixed effects. All visual control ratings were arranged as repeated measures. Type III statistics were used to test all possible interactions of these fixed effects. Tukey's test was used to separate means at the 5% probability level ($p \leq 0.05$).

Results and Discussion

A benzobicyclon rate interaction was observed for yellow nutsedge plant height, leaf number, and tuber number; therefore, data were averaged over evaluation date and flood depth (Table 4.1). Yellow nutsedge plants treated with benzobicyclon at 493 g ai ha^{-1} were 42 cm in height and shorter when compared with the height of nontreated plants; however, no difference occurred for plant height, 47 to 51-cm, with yellow nutsedge treated with any other benzobicyclon rate evaluated.

Total leaf number of yellow nutsedge plants treated with benzobicyclon at 493 and 1968 g ha^{-1} was 4.4 and 4.0, respectively, and these treatments were lower in leaf numbers compared with nontreated yellow nutsedge plants with 6.4 leaves (Table 4.1). Plants receiving any other rate of benzobicyclon had leaf numbers that did not differ compared with the nontreated; however, no difference occurred for leaf number, 4.8 to 4.9, with yellow nutsedge treated with any other benzobicyclon rate evaluated.

Yellow nutsedge plants receiving any rate of benzobicyclon had fewer tubers than nontreated plants (Table 4.1). Nelson and Renner (2002) observed a reduction in yellow nutsedge tuber production with glyphosate and ALS-inhibiting herbicides. Tuber production is the primary means of yellow

Table 4.1. Impact of benzobicyclon application rates on yellow nutsedge plant height, leaf number, and tuber number, averaged over evaluation timing and flood depths.[abc]

Benzobicyclon rate	Height[d]	Leaf	Tuber
— g ai ha^{-1} —	— cm —	——— number	———
0	61 a	6.4 a	3.6 a
246	47 ab	4.8 ab	1.5 b
493	42 b	4.4 b	0.9 b
984	51 ab	4.9 ab	1.2 b
1476	48 ab	4.8 ab	0.7 b
1968	47 ab	4.0 b	0.6 b

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Study was conducted in October 2013 and repeated in December 2014.
[c]Means averaged across 5- and 10-cm flood depth treatments 14, 21, and 28 DAT.
[d]Height measurements were taken from the soil level to the tip of the tallest extended leaf.

nutsedge propagation (Stoller and Sweet 1987) and by reducing tuber production, benzobicyclon could be useful in reducing future populations of yellow nutsedge.

A flood depth effect was observed on yellow nutsedge leaf number; therefore, data were averaged over herbicide rate and evaluation timing (Table 4.2). Plants grown in a 10-cm flood had a leaf number of 4.2. This was reduced compared with the leaf number of plants grown in the 5-cm flood, which had 5.5 leaves per plant. Compared with barnyardgrass which is not effected by flood depth (Masson et al. 2001), a deep flood often increases control of *Cyperus* spp. and reduces competiveness of this weed in rice (Chauhan and Johnson 2009; Williams et al. 1990)

The above-ground yellow nutsedge biomass was not significant; however, a herbicide rate interaction occurred for below-ground plant weight and total

Table 4.2. Impact of flood depth on yellow nutsedge plant leaf number, averaged over benzobicyclon rate and evaluation timing.[ab]

Flood depth	Leaf
—— cm ——	—— number ——
5	5.5 a
10	4.2 b

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Runs conducted in October 2013 and December 2014.

plant weight, therefore, data were averaged over flood depth of 5- and 10-cm (Table 4.3). Yellow nutsedge treated with benzobicyclon at 246, 493, and 1968 g ha^{-1} reduced below-ground weight and total weight compared with the nontreated. Below-ground or total plant weight was not reduced compared with the nontreated plants for yellow nutsedge plants treated with benzobicyclon at 984 and 1476 g ha^{-1}. While above-ground biomass was not impacted, below-ground reduction may play a role in reducing yellow nutsedge vigor and competitiveness with rice, and reduce future yellow nutsedge populations through reduced propagation (Webster 2008). Harvested tubers were porous and lacked the normal integrity of non-injured yellow nutsedge tubers; therefore, tubers were determined to be non-viable and were not planted in a subsequent trial to evaluate impact of benzobicyclon application on tuber germination viability.

An evaluation timing interaction was observed for yellow nutsedge bleaching; therefore, data were averaged over benzobicyclon rate and flood depth (Table 4.4). Yellow nutsedge bleaching symptoms increased in severity at each evaluation timing. Phytotoxicity averaged over benzobicyclon rates and flood depth at 14 DAT was 27%. Injury increased to 36% by 21 DAT and reached the highest level of bleaching, 43%, at 28 DAT; however, visual

Table 4.3. Impact of benzobicyclon herbicide treatment on yellow nutsedge below-ground fresh weight and total plant fresh weight, averaged over flood depths 5- or 10-cm.[ab]

	Weight		
Benzobicyclon rate	Above-ground	Below-ground	Total Plant
— g ai ha^{-1} —	g		
0	3.9	4.8 a	8.6 a
246	2.8	2.8 b	5.5 b
493	2.6	2.2 b	4.8 b
984	3.0	3.2 ab	6.1 ab
1476	2.6	3.1 ab	5.8 ab
1968	2.7	2.4 b	5.0 b
	ns		

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Study was conducted in October 2013 and repeated in December 2014.

Table 4.4. Impact of evalution timing on bleaching of yellow nutsedge foliage, averaged over benzobicyclon rate and flood depth.[abcd]

Evaluation timing	Phytotoxicity
– DAT[e] –	— % bleaching —
14	27 c
21	36 b
28	43 a

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Runs conducted in October 2013 and repeated in December 2014.
[c]Benzobicyclon applied at 0, 246, 493, 984, 1476, and 1968 g ha^{-1}.
[d]Flood depth: 5- and 10-cm.
[e]Abbreviation: DAT, days after treatment.

injury never exceeded 50%, indicating activity of benzobicyclon on yellow nutsedge was minimal. The time in which bleaching symptoms were first observed and the progression of the symptoms and level of control were similar to observations of yellow nutsedge plants treated with benzobicyclon in field research studies (McKnight at al. 2014).

The activity of benzobicyclon in this glasshouse study did not result in complete plant death from any rate applied. Benzobicyclon treatment at any rate provided suppression of tuber production, which may inhibit the reproductive success of future populations of yellow nutsedge. Nelson and Renner (2002) observed decreased yellow nutsedge tuber production when plants were treated with glyphosate or ALS inhibiting herbicides and reduction in tuber viability was documented by Webster et al. (2008). Any tubers present on yellow nutsedge plants treated with benzobiyclon were deemed not viable at the conclusion of these glasshouse trials, and were abnormally shaped and beginning decomposition. Benzobicyclon applied at 493 and 1968 g ha^{-1} reduced leaf number compared with the nontreated plants. The reduction in plant leaf number and below-ground tissue following benzobicyclon application may reduce yellow nutsedge competitiveness with crop plants (Thullen and Keeley 1979; Patterson 1982). Young et al. (2015) concluded that a pre-packaged mixture of halosulfuron plus benzobicyclon would provide an option for yellow nutsedge control in rice production. Based on the control observed in this and other field trials, benzobicyclon would not be specifically recommended for control of yellow nutsedge in Louisiana; however, when applied to rice for the control of other target species this product may have an impact on yellow nutsedge populations in future growing seasons. Halosulfuron applied alone controls yellow nutsedge 97% (Nelson and Renner 2002), and the addition of halosulfuron, either in a co-application or formulated as a pre-packaged mixture could increase activity on yellow nutsedge activity.

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Chapter 5

Benzobicyclon Applied in Mixture with Imazethapyr and Imazamox

Introduction

Imidazolinone-resistant (IR) rice was developed in 1993 by means of seed mutagenesis (Croughan 1994). This technology is a non-transgenic trait and confers resistance to imidazolinone herbicides in rice lines available for commercial production. The development of IR rice allows selective chemical control of red rice in commercial rice fields (Masson and Webster 2001; Pellerin et al. 2004; Webster and Masson 2001), and imidazolinone herbicides exhibit broad-spectrum weed control with soil and foliar activity (Stougaard et al. 1990). Imidazolinone herbicides are included in a large group of herbicides that inhibit acetolactate synthase (ALS) (EC 4.1.3.18) (Shaner 2014; Stidham and Singh 1991). Imazethapyr and imazomox are two imidazolinone herbicides composing the Clearfield® (BASF Corporation, Research Triangle Park, NC) rice production system and are labeled for use in IR rice varieties at application rates of 70 to 105 g ai ha^{-1} and 35 to 53 g ai ha^{-1}, respectively (Webster 2014).

The adoption of IR rice technology broadened the flexibility of tillage and cultural practices by offering an effective means of red rice control in a drill-seeded production system. Prior to IR rice, water-seeding practices were utilized as an effective way to reduce red rice competition with cultivated rice by creating an environment that reduces red rice germination (Levy et al. 2006; Sonnier and Baker 1980). Drill-seeded plantings increased significantly over water-seeded plantings in Louisiana following the adoption of IR rice (Harrell 2016). Timely water management following imazethapyr application in drill-seeded rice plantings is still essential for acceptable weed control and avoiding yield loss to weed competition (Avila et al. 2005).

Several broadleaf and grass weeds infest rice culture (Braverman 1995). Common weeds in Mid-South U.S. rice production include barnyardgrass

[*Echinochloa crus-galli* (L.) P. Beauv], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], yellow nutsedge (*Cyperus esculentus L.*), *Aeschynomene spp*., hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], ducksalad [*Heteranthera limosa* (Sw.) Willd.], and *Leptochloa spp*. (Webster 2011). Several of these common weeds are not controlled with imidazolinone herbicides (Ottis et al. 2002; Richburg et al. 1995; Webster et al. 2012; Webster and Masson 2001; Zhang et al. 2001) Growers can broaden weed control spectrum and reduce costs associated with application by mixing two or more herbicides into one spray solution (Hydrick and Shaw 1994). The use of herbicides with different modes of action mixed into a single spray mixture can be an important component in a herbicide resistance management program (Norsworthy et al. 2012).

If herbicide mixtures that interact in such a way that weed control is improved compared with the effect of each product applied independently, the effect is deemed synergistic. Fish et al. (2015) observed a synergistic response on barnyardgrass and red rice when imazethapyr was applied in a single spray solution with a pre-packaged mixture of propanil plus thiobencarb. A synergistic response was also observed on red rice when imazamox was mixed with propanil (Fish et al. 2016). The increased activity along with the utilization of multiple modes of action can be beneficial to weed resistance management practices.

Benzobicyclon is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) (EC 1.13.11.27) inhibiting herbicide that has been labeled for use in Japan since 2001 (Komatsubara et al. 2009). Sekino et al. (2008) observed both preemergence (PRE) and postemergence (POST) benzobicyclon activity on susceptible weeds when applied at rates of 200 to 300 g ai ha^{-1}. Little or no phytotoxicity was observed in rice plants when applied at 600 g ha^{-1}. The primary symptom of benzobicyclon herbicide injury on susceptible weed species is bleaching of plant tissue followed by chlorosis and complete plant death

(Komatsubara et al. 2009). The primary route of benzobicyclon uptake occurs via root and shoot tissue and control of susceptible weed species is observed 8 weeks after treatment, indicating favorable residual control characteristics (Sekino et al. 2008). Field studies evaluating benzobicyclon plus imidazolinone herbicides are not found in the literature. IR rice accounted for approximately 61% of the total rice hectarage in Louisiana in 2016 (Harrell 2016). This study was conducted to evaluate the potential weed management benefits benzobicyclon provides to imidazolinone herbicides when applied in mixture on IR rice.

Materials and Methods

Field studies were conducted in 2013 and 2014 at the Louisiana State University Agricultural Center H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana on a Midland silty clay loam (fine, smectitic, thermic Chromic Vertic Epiaqualf) with 1.2% organic matter and pH 6.1. Seedbed preparation included a fall and spring disking followed by two perpendicular passes with a two-way bed conditioner employing S-tine harrows, set at a 10-cm depth, and rolling baskets. ‘CL 111’ IR rice seed was drill-seeded for sequential imazethapyr followed by (fb) imazethapyr and sequential imazethapyr fb imazamox field studies on April 23, 2013 and April 16, 2014. Following planting, 1.5 by 5.2 m^2 plots were established and 91-cm diameter by 30-cm tall galvanized metal rings were placed at random near the center of each plot and pressed firmly into the soil approximately 5-cm to seal the area contained inside the ring from the rest of the plot area. Sekino et al. (2008) observed increased activity of benzobicyclon when applied directly to flood water, and the galvanized metal ring was used to allow for herbicide containment without the need for individually-leveed plots. Weed evaluations were only taken within the ring; however, the entire plot area, 1.5 by 5.2 m^2, was treated. Fertility and other pest management practices were based on recommendations from the LSU AgCenter Rice Production Guidelines (Harrell and Saichuk 2014).

Two separate studies were conducted to evaluate two common IR production systems utilized in Louisiana. In one study, imazethapyr (Newpath herbicide label, BASF Corporation, Research Triangle Park, NC) was applied as a sequential two-application program and benzobicyclon (Gowan Company, Yuma, Arizona) was mixed with one imazethapyr application at different timings (Table 5.1). In the second study, imazethapyr fb imazamox (Beyond herbicide label, BASF Corporation, Research Triangle Park, NC) were applied as a sequential two-application program with benzobicyclon mixed with either imazethapyr or imazamox at different timings (Table 5.2). The study design for both field trials was a randomized complete block design replicated four times. Herbicide applications were made utilizing a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} spray solution at 190 kPa. Crop-oil-concentrate (COC) (Agri-Dex® label, Helena Chemical Company, Collierville, TN) was added to all treatments at 1% v v^{-1}.

In 2013, both studies were surface irrigated every 7 days after planting and prior to the establishment of the 10-cm permanent flood on June 4. In 2014 studies, both studies were surface irrigated every 7 days after planting and prior to the establishment of the 10-cm permanent flood on June 5. Weed sizes at time of application in 2013 and 2014 field trials are listed in Table 5.3.

Visual control ratings of hemp sesbania, yellow nutsedge and barnyardgrass were collected 14, 28, and 42 DAT. Visual weed control ratings were assigned on a scale of 0 to 100%, where 0 = no injury and 100 = complete plant death. The center four rows of rice were harvested with a Mitsubishi® VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2-chome, Chiyoda-ky, Tokyo,

Table 5.1. Treatment list for imazethapyr fb imazethapyr with the addition of benzobicyclon.

Treatments[ab]	Rate	Timing[b]
	– g ha^{-1} –	
Imazethapyr fb	105	EPOST
imazethapyr	70	LPOST
Imazethapyr +	105	EPOST
benzobicyclon fb	246	EPOST
imazethapyr	70	LPOST
Imazethapyr fb	105	EPOST
imazethapyr +	70	LPOST
benzobicyclon	246	LPOST
Imazethapyr fb	105	EPOST
imazethapyr	70	PREFLOOD
Imazethapyr fb	105	EPOST
imazethapyr +	70	PREFLOOD
benzobicyclon	246	PREFLOOD
Imazethapyr fb	105	EPOST
imazethapyr	70	POSTFLOOD
Imazethapyr fb	105	EPOST
imazethapyr +	70	POSTFLOOD
benzobicyclon	246	POSTFLOOD

[a]All herbicide treatments applied with 1% v v^{-1} COC.
[b]Abbreviations: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment.

Table 5.2. Treatment list for imazethapyr fb imazamox with the addition of benzobicyclon.

Treatments[ab]	Rate	Timing[b]
	– g ha^{-1} –	
Imazethapyr fb	105	EPOST
imazamox	44	LPOST
Imazethapyr +	105	EPOST
benzobicyclon fb	246	EPOST
imazamox	44	LPOST

Table 5.2 continued.

Table 5.2 continued.

Treatments[ab]	Rate	Timing[b]
	– g ha^{-1} –	
Imazethapyr fb	105	EPOST
imazamox +	44	LPOST
benzobicyclon	246	LPOST
Imazethapyr fb	105	EPOST
imazamox	44	PREFLOOD
Imazethapyr fb	105	EPOST
imazamox +	44	PREFLOOD
benzobicyclon	246	PREFLOOD
Imazethapyr fb	105	EPOST
imazamox	44	POSTFLOOD
Imazethapyr fb	105	EPOST
imazamox +	44	POSTFLOOD
benzobicyclon	246	POSTFLOOD
Imazethapyr fb	105	EPOST
imazamox	44	PI
Imazethapyr fb	105	EPOST
imazamox +	44	PI
benzobicyclon	246	PI

[a]All herbicide treatments applied with 1% v v^{-1} COC.
[b]Abbreviations: fb, followed by; EPOST applied on two -to three-leaf rice; LPOST applied on five -leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment; PI application applied when rice reached panicle initiation stage.

Japan) rice harvester at the conclusion of the study and rough rice grain weight was adjusted to 12% moisture for yield determination.

Data were arranged as repeated measures and subjected to the mix procedure of SAS (release 9.4, SAS Institute, Cary, NC). Location, years, replication (nested within year) and all interactions including any of these effects were considered random effects. Considering year or combination of year as random effects permits inferences about treatments over a range of environments (Carmer et al. 1989; Hager et al. 2003). Herbicide treatment and rating date was considered a fixed effect. Type III statistics were used to

Table 5.3. Weed size and growth stage at time of herbicide application in 2013 and 2014.

Timing[a]	Barnyardgrass		Hemp sesbania		Yellow nutsedge	
	Growth stage[a]	cm	Growth stage	cm	Growth stage	cm
EPOST	2 lf-1 till	3-18	3-6 lf	5-12	3-9 lf	12-20
LPOST	3 lf-2 till	8-25	4-8 lf	10-20	3-12 lf	12-25
PREFLOOD	5 lf-3 till	10-35	10-12 lf	15-30	6-15 lf	15-40
POSTFLOOD	5 lf-3 till	10-35	10-12 lf	15-30	6-15 lf	15-40
PI	2-4 till	40-60	12-18 lf	30-60	9-15 lf	30-50

[a]Abbreviations: lf, leaf; till, tiller; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment;, POSTFLOOD applied 24 h following permanent flood establishment; PI applied when rice reached panicle initiation stage.

test all possible interactions of these fixed effects. Tukey’s test was used to separate means at the 5% probability level ($p \leq 0.05$).

Results and Disscussion

In the study evaluating benzobicyclon mixed with imazethapyr in a sequential two-application program, a herbicide treatment interaction was observed for barnyardgrass and hemp sesbania control; therefore, data were averaged across evaluation timings (Table 5.4). Imazethapyr applied EPOST at 105 g ai ha^{-1} fb imazethapyr applied LPOST at 70 g ha^{-1} controlled barnyardgrass 86%. The addition of benzobicyclon did not increase barnyardgrass over the sequential imazethapyr treatment when applied prior to permanent flood establishment. The barnyardgrass control observed in this research is similar to others (Masson and Webster 2001; Ottis et al. 2003; Pellerin et al. 2004). Barnyardgrass control decreased by delaying the second imazethapyr application to a POSTFLOOD timing. The addition of benzobicyclon

Table 5.4. Control of barnyardgrass and hemp sesbania with sequential imazethapyr program with with and without benzobicyclon in imidazolinone-resistant rice, averaged over evaluation timing.[ab]

Treatment[c]	Rate	Timing[c]	Control[d]	
			Barnyardgrass	Hemp sesbania
	g ha^{-1}		%	
Imazethapyr fb imazethapyr	105 70	EPOST LPOST	86 a	9 b
Imazethapyr + benzobicyclon fb imazethapyr	105 246 70	EPOST EPOST LPOST	84 a	29 a
Imazethapyr fb imazethapyr + benzobicyclon	105 70 246	EPOST LPOST LPOST	84 a	28 a
Imazethapyr fb imazethapyr	105 70	EPOST PREFLOOD	83 a	16 ab
Imazethapyr fb imazethapyr + benzobicyclon	105 70 246	EPOST PREFLOOD PREFLOOD	86 a	23 ab
Imazethapyr fb imazethapyr	105 70	EPOST POSTFLOOD	62 b	16 ab
Imazethapyr fb imazethapyr + benzobicyclon	105 70 246	EPOST POSTFLOOD POSTFLOOD	55 b	24 a

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test within columns.
[b]Field trials conducted in 2013, 2014 and 2015.
[c]Abbreviation: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment.
[d]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

POSTFLOOD did not increase control of barnyardgrass compared with the imazethapyr only program.

A slight increase in hemp sesbania control was observed with the addition of benzobicyclon applied with the EPOST and LPOST imazethapyr timing; however, control was below 30% for any mixture evaluated. The hemp sesbania control observed is similar to those reported by Klingman et al. (1992) and Pellerin et al. (2004).

An evaluation timing interaction occurred for barnyardgrass and hemp sesbania control; therefore, data were averaged over herbicide treatment (Table 5.5). Control for both, barnyardgrass and hemp sesbania, increased as evaluation date extended beyond 14 DAT (Table 5.5). This indicates that both herbicides, imazethapyr and benzobicyclon, require 14 to 21 DAT to achieve maximum control, and this is similar to research reported for imazethapyr (Masson et al. 2001) and benzobicyclon (McKnight et al. 2014).

A herbicide treatment by evaluation date interaction occurred for yellow nutsedge control (Table 5.6). Imazethapyr applied EPOST at 105 g ha^{-1} followed by imazethapyr at 70 g ha^{-1} applied at 24 h POSTFLOOD resulted in reduced yellow nutsedge control of 73% when compared with 28 and 42 DAT for the same treatment. By delaying the final application of imazethapyr to a POSTFLOOD timing, yellow nutsedge was larger and partially covered by flood water causing a delay in control (Table 5.3). The delay to POSTFLOOD did not differ from the PREFLOOD timing of imazethapyr regardless of the addition of benzobicyclon. In each case, yellow nutsedge was larger than when it was treated EPOST or LPOST. These data indicate in order for effective control, yellow nutsedge treatment with imazethapyr should be applied in a timely manner to small actively growing yellow nutsedge, and this is similar to findings with barnyardgrass (Pellerin and Webster 2004). The addition of benzobicyclon did not aid in the management of yellow nutsedge in a IR rice production system.

A herbicide treatment interaction occurred for rough rice yield (Table 5.7). Imazethapyr applied EPOST provided weed control and reduced competition from weeds early in the growing season. Rice treated with imazethapyr applied EPOST fb imazethapyr LPOST yielded 269% of the nontreated. No yield difference was observed from rice treated with imazethapyr fb imazethapyr

Table 5.5. Control of barnyardgrass and hemp sesbania in sequential imazethapyr program with benzobicyclon in imidazolinone-resistant rice, averaged over herbicide treatment.[ab]

	Control[c]	
Evaluation Timing	Barnyardgrass	Hemp sesbania
(DAT)	%	
14	72 b	15 b
28	78 a	23 a
42	81 a	23 a

[a]Imazethapyr applied at 105 EPOST fb 70 g ha^{-1} LPOST, PREFLOOD, or POSTFLOOD, benzobicyclon applied at 246 g ha^{-1}.
[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test within columns.
[b]Field trials conducted in 2013, 2014 and 2015.
[c]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

Table 5.6 Control of yellow nutsedge in sequential imazethapyr program with benzobicyclon at different evalutation timings.[ab]

			yellow nutsedge control[d]		
Treatment[c]	Rate	Timing[c]	14 DAT	28 DAT	42 DAT
	– g ha^{-1} –		%		
Imazethapyr fb imazethapyr	105 70	EPOST LPOST	90 a	95 a	93 a
Imazethapyr + benzobicyclon fb imazethapyr	105 246 70	EPOST EPOST LPOST	94 a	93 a	93 a
Imazethapyr fb imazethapyr + benzobicyclon	105 70 246	EPOST LPOST LPOST	93 a	94 a	94 a
Imazethapyr fb imazethapyr	105 70	EPOST PREFLOOD	82 ab	94 a	93 a
Imazethapyr fb imazethapyr + Benzobicyclon	105 70 246	EPOST PREFLOOD PREFLOOD	85 ab	93 a	93 a

Table 5.6 continued.

Table 5.6 continued.

Treatment[c]	Rate	Timing[c]	yellow nutsedge control[d] 14 DAT	28 DAT	42 DAT
	– g ha^{-1} –		%		
Imazethapyr fb	105	EPOST	73 b	90 a	90 a
imazethapyr	70	POSTFLOOD			
Imazethapyr fb	105	EPOST	91 a	89 a	92 a
imazethapyr +	70	POSTFLOOD			
benzobicyclon	246	POSTFLOOD			

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test within columns and across rows.
[b]Field trials conducted in 2013, 2014 and 2015.
[c]Abbreviations: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment.
[d]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

Table 5.7. Rough rice yield from rice treated with sequential imazethapyr programs with benzobicyclon.[ab]

Treatment[c]	Rate	Timing[c]	Rice Yield	
	– g ha^{-1} –		— kg ha^{-1} —	% nontreated
nontreated	—	—	2410 b	—
Imazethapyr fb	105	EPOST	6490 a	269
imazethapyr	70	LPOST		
Imazethapyr +	105	EPOST	6230 a	259
benzobicyclon fb	246	EPOST		
imazethapyr	70	LPOST		
Imazethapyr fb	105	EPOST	5640 a	234
imazethapyr +	70	LPOST		
benzobicyclon	246	LPOST		
Imazethapyr fb	105	EPOST	5830 a	242
imazethapyr	70	PREFLOOD		

Table 5.7 continued.

Table 5.7 continued.

Treatment[c]	Rate	Timing[c]	Rice Yield	
	– g ha^{-1} –		— kg ha^{-1} —	% nontreated
Imazethapyr fb	105	EPOST	5180 a	215
imazethapyr +	70	PREFLOOD		
benzobicyclon	246	PREFLOOD		
Imazethapyr fb	105	EPOST	5780 a	240
imazethapyr	70	POSTFLOOD		
Imazethapyr fb	105	EPOST	6260 a	260
imazethapyr +	70	POSTFLOOD		
benzobicyclon	246	POSTFLOOD		

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey's test.
[b]Years: 2013 and 2014.
[c]Abbreviations: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment.

regardless of the addition of benzobicyclon, and rice treated with any herbicide program evaluated yielded at least 215% of the nontreated rice.

In the study evaluating benzobicyclon mixed with imazethapyr or imazamox in a two-application program, a significant herbicide treatment interaction was observed for hemp sesbania, barnyardgrass, and yellow nutsedge; therefore, data were averaged over evaluation date for all weeds evaluated (Table 5.8). Imazethapyr at 105 g ha^{-1} applied EPOST followed by imazamox at 44 g ha^{-1} applied LPOST controlled barnyardgrass 90%, which is similar to control on barnyardgrass reported by Webster et al. (2012) from early imazethapyr fb imazamox applications. The addition of benzobicyclon did not increase barnyardgrass control over imazethapyr applied EPOST fb imazamox applied LPOST, PREFLOOD, or POSTFLOOD. However, a decrease in barnyardgrass control, 66%, was observed by delaying the imazamox application to the PI timing, and the addition of benzobicyclon at the PI timing increased

Table 5.8. Control of barnyardgrass, hemp sesbania and yellow nutsedge in imazethapyr followed by imazamox program with benzobicyclon, averaged across evaluation timing.[ab]

Treatment[c]	Rate	Timing[c]	Control[d]		
			Barnyardgrass	Hemp sesbania	Yellow nutsedge
	g ha^{-1}		%		
Imazethapyr fb imazamox	105 44	EPOST LPOST	90 a	10 cd	94 a
Imazethapyr + benzobicyclon fb imazamox	105 246 44	EPOST EPOST LPOST	89 a	14 bcd	96 a
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST LPOST LPOST	87 a	24 ab	96 a
Imazethapyr fb imazamox	105 44	EPOST PREFLOOD	88 a	5 d	93 ab
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST PREFLOOD PREFLOOD	89 a	26 a	96 a
Imazethapyr fb imazamox	105 44	EPOST POSTFLOOD	81 ab	13 cd	88 ab
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST POSTFLOOD POSTFLOOD	82 ab	28 a	94 a
Imazethapyr fb imazamox	105 44	EPOST PI	66 c	8 cd	82 b
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST PI PI	72 bc	15 bc	89 ab

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test within columns.

[b]Field trials conducted in 2013, 2014 and 2015.

[c]Abbreviations: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment; PI applied when rice reached panicle initiation stage.

[d]Control was measured using a scale of 0 (no control) to 100 (complete control) based on visual symptoms.

barnyardgrass control, 72%, to levels observed with imazamox applied POSTFLOOD.

An increase in hemp sesbania control was observed when benzobicyclon was mixed with imazamox except for the PI timing (Table 5.8). This increase was slight and hemp sesbania control did not exceed 30% from any herbicide treatments, and this further indicates an additional herbicide will be needed to manage hemp sesbania in an IR production system. Pellerin et al. (2004) reported an increase in hemp sesbania control when halosulfuron was mixed with imazethapyr. Young et al. (2015) concluded that a mixture of halosulfuron plus benzobicyclon would be an effective control option for hemp sesbania in rice production.

Imazethapyr applied EPOST fb imazamox LPOST controlled yellow nutsedge 94% (Table 5.8). The addition of benzobicyclon did not increase yellow nutsedge control over the sequential imazamox treatment applied alone prior to the PI application. Yellow nutsedge control decreased by delaying the imazamox application at PI when compared with earlier imazamox mixed with benzobicyclon application timings; however, the addition of benzobicyclon with imazamox at the PI timing did increase yellow nutsedge control, 89%, to levels similar to imazethapyr fb imazamox LPOST, 94%, at this application timing.

A herbicide interaction occurred for rough rice yield (Table 5.9). No difference in rough rice yield was observed with rice treated with any herbicide program; however, rice treated with imazethapyr EPOST fb imazamox plus benzobicyclon LPOST increased rough rice yield compared with the nontreated. This indicates benzobicyclon may be useful in an early season application with imazamox, and this increase may be due to reduced competition of barnyardgrass, hemp sesbania, and yellow nutsedge even though control was not increased over an imazethapyr plus imazamox program. The

Table 5.9. Rough rice yield from rice treated with imazethapyr followed by imazamox programs plus benzobicyclon.[ab]

Treatment[c]	Rate	Timing[c]	Rice Yield	
	— g ha^{-1} –		— kg/ha —	% of nontreated
nontreated	—	—	3990 b	—
Imazethapyr fb imazamox	105 44	EPOST LPOST	5410 ab	136
Imazethapyr + benzobicyclon fb imazamox	105 246 44	EPOST EPOST LPOST	5180 ab	130
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST LPOST LPOST	6180 a	155
Imazethapyr fb imazamox	105 44	EPOST PREFLOOD	6400 a	160
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST PREFLOOD PREFLOOD	5600 ab	140
Imazethapyr fb imazamox	105 44	EPOST POSTFLOOD	6650 a	167
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST POSTFLOOD POSTFLOOD	6270 a	157
Imazethapyr fb imazamox	105 44	EPOST PI	6590 a	165
Imazethapyr fb imazamox + benzobicyclon	105 44 246	EPOST PI PI	6770 a	170

[a]Means followed by the same letter do not significantly differ at P=0.05 using Tukey’s test.

[b]Years: 2013 and 2014.

[c]Abbreviations: fb, followed by; EPOST applied on two- to three-leaf rice; LPOST applied on five- leaf to one-tiller rice; PREFLOOD applied 24 h prior to permanent flood establishment; POSTFLOOD applied 24 h following permanent flood establishment; PI applied when rice reached panicle initiation stage.

addition of benzobicyclon mixed with a PREFLOOD, POSTFLOOD, or PI timing did not benefit from an increase in yield compared with the imazethapyr plus imazamox programs with the later application timings.

IR rice accounted for 61% of the total Louisiana rice crop in 2016 (Harrell 2016). Imazethapyr and imazamox are the two ALS inhibiting herbicides labeled for use on IR rice (Webster 2014). These herbicides provide control of red rice, key grass weeds, and some broadleaf weeds in-crop; however, imazethapyr and imazamox do not provide adequate control of hemp sesbania (Klingman et al. 1992; Pellerin et al. 2004). Herbicides with activity on this weed can be mixed with imazethapyr or imazamox to broaden the weed control spectrum. While an increase in hemp sesbania control with the addition of benzobicyclon at some application timings was observed, the increase was minimal and control never exceeded 30%. Benzobicyclon mixed with a sequential application of imazamox was similar to mixtures with imazethapyr and control never exceeded 30%.

Sequential applications of imazethapyr applied alone provided barnyardgrass control that was similar to that observed in previous research (Masson et al. 2001; Ottis et al. 2003; Pellerin et al. 2004). When benzobicyclon was mixed with imazethapyr on barnyardgrass no benefits in control were observed. Benzobicyclon mixed with imazethapyr or imazamox in a sequential application did not increase yellow nutsedge control over imazethapyr or imazamox programs. Rice yield was higher when rice was treated with imazethapyr compared with the nontreated in the sequential imazethapyr program trial. The addition of benzobicyclon to imazethapyr or imazamox did not affect yield compared with imazethapyr or imazamox applied alone. The results from these studies indicates benzobicyclon is not an effective mix partner for the control of hemp sesbania in the Clearfield® herbicide programs and do not enhance barnyardgrass or yellow nutsedge activity over standard sequential programs utilized in Louisiana IR production.

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Chapter 6

Summary

Benzobicyclon is a 4-hydroxyphenylpyruvate dioxygenase (HPPD) (EC 1.13.11.27) inhibiting herbicide that has been labeled for use in Japan since 2001 (Komatsubara et al. 2009), and benzobicyclon is marketed there in several different formulations and pre-packaged mixtures. Symptoms on susceptible weeds following benzobicyclon application are bleaching of plant tissue, followed by severe chlorosis and eventual plant death. Sekino et al. (2008) observed both preemergence (PRE) and postemergence (POST) activity on troublesome weeds in rice production in Japan. Rates of 200 to 300 g ai ha^{-1} controlled several weed species from both, PRE applications on soil and early POST applications, directly in flood irrigation water. This research also concluded that benzobicyclon controlled weeds 8 weeks after treatment. Residual control is a favorable component and can extend weed free periods that are essential to crop establishment and maximized yields through reduced weed competition (Smith 1968; 1974; 1983; 1984; 1988). No phytotoxicity was observed on rice following benzobicyclon applied at 600 g ha^{-1} which indicates rice has excellent crop safety when treated with this herbicide. Komatsubara et al. (2009) analyzed rice plant tissue and found that 3% benzobicyclon was absorbed into the rice plant and none translocated to the grain.

Benzobicyclon is active on a diverse spectrum of weed species common in Japan including *Monochoria vaginalis* [(Burm. f.) C. Presl. ex Kunth], *Schoenoplectus juncoides* [(Roxb.) Palla], *Cyperus serotinus* (Rott.), *Sagittaria pygmaea* (Miq.), and *Lindernia dubia* [(L.) Pennell var. dubia]. Many common weeds of Louisiana rice production systems are taxonomically classified within the same genus as those found in Japan that are controlled by benzobicyclon (Webster 2014). Several aquatic weed species in Louisiana rice production become troublesome when rice fields are rotated with crawfish production systems (Webster 2014). Past ecotoxicological studies have demonstrated little to no activity on soil microorganisms, birds, algae, and insects (Komatsubara et al. 2009). These favorable toxicological characteristics of benzobicyclon are especially desirable for growers rotating rice fields with crawfish production in Louisiana.

Water-seeded rice plantings accounted for 35% of total Louisiana rice crop in 2016 (Harrell 2016). Because water is introduced to these production systems earlier in the growing season compared with dry-seeded plantings, aquatic weeds can become competitive much earlier in the growing season (Smith 1968). Ducksalad [*Heteranthera limosa* (Sw.) Willd.] is a common, early-season nuisance in Louisiana water-seeded production and control from herbicides is usually only accomplished when effective compounds are applied to ducksalad foliage following a lowering of flood irrigation water (Sankula et al. 1997; Webster 2014). The unique activity of benzobicyclon when applied directly to flood water is a promising herbicide for ducksalad control. Currently, HPPD inhibiting herbicides are not labeled for use in U.S. rice production and the adoption of benzobicyclon could benefit an overall resistant management program (Norsworthy et al 2012).

Field studies were conducted in the 2013, 2014, and 2015 growing seasons at the LSU AgCenter H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to determine the response of benzobicyclon on weeds when applied at different timings in a water-seeded production system. Benzobicyclon treatments of 246 g ha^{-1} were applied at 7 different timings in a water-seeded system utilizing a pinpoint flood. The herbicide application timings were: preplant onto dry soil (SURFACE), into the seeding flood 24 h after seeding (SEED), 24 h after the draining of the seeding flood (POSTSEED), on pegging rice 24 h prior to the pinpoint flood establishment (PEG), 24 h following the establishment of the pinpoint flood (PIN), on three- to four-leaf rice or mid-postemergence (MPOST), and one- to two-tiller rice or late-postemergence (LPOST). All plots contained a 91-cm diameter by

30-cm tall galvanized metal ring, pressed into the soil 5-cm, near the center of the plot for benzobicyclon treatment containment. Visual weed control ratings of barnyardgrass, yellow nutsedge and ducksalad were recorded at 21, 35, and 49 DAT within each ring. Rice plant heights were recorded immediately prior to harvesting and the center 0.75 by 3.6 m of each plot were harvested with a mechanical rice harvester.

Benzobicyclon applied at the PEG and PIN timing controlled barnyardgrass 97 and 94%, respectively, and control of barnyardgrass increased at later evaluation timings. Yellow nutsedge control of 95% was observed at 21 DAT when benzobicyclon was applied at the PEG application timing. At 35 and 49 DAT, yellow nutsedge control from benzobicyclon application at the PEG timing was 98 and 97%, respectively. By 49 DAT, control of ducksalad when treated with benzobicyclon at the SURFACE and PIN timing was 93 and 95%, respectively, and was higher when compared with ducksalad control from the PEG timing with 69%. Ducksalad control was greater than 90% at all evaluation timings when treated with benzobicyclon applied at the PIN timing, indicating early application into the permanent flood is needed to achieve the most consistent ducksalad control. These data suggest benzobicyclon should be applied to small actively growing weeds and immediately prior to, or following, the establishment of the permanent flood in water-seeded plantings.

A field study was conducted at RRS near Crowley, Louisiana in 2013, 2014, 2015 and 2016 on two different soils, and at the LSU AgCenter Northeast Research Station (NERS) near St. Joseph, Louisiana in 2015 to determine the rate response of common Louisiana rice weeds to benzobicycon applied at nine different rates. Water management in this study was the same as a water-seeded system; however, no rice was planted in this study to eliminate competition with a naturally occurring weed infestation. All plots contained a 91-cm diameter by 30-cm tall galvanized metal ring for benzobicyclon treatment containment. Benzobicyclon was applied at 0, 31, 62, 123, 185, 246, 493, 739, 986 and 1232 g ha^{-1}. Visual weed control ratings were recorded at 7, 21, 35, and 49 DAT. At the conclusion of the study, all weed biomass from the containment ring was hand-harvested and separated by species for fresh weight determination.

Control of yellow nutsedge, false pimpernel, and barnyardgrass did not exceeded 50% from any rate of benzobicyclon applied. An evaluation timing interaction was observed for these species and barnyardgrass began to recover from 14 to 28 DAT. The reduction of symptoms also occurred on yellow nutsedge plants between 28 and 42 DAT, suggesting these species are tolerant to benzobicyclon when treated at a large size and are actively growing. Indian toothcup control was 99% at 28 and 42 DAT following treatment with benzobicyclon rates of 493 g ha^{-1} and higher. Ducksalad treated with benzobicyclon at 493 g ha^{-1} was controlled 83 to 93% with no difference observed when applied at rates of 493 to 1232 g ha^{1}. Ducksalad fresh weight was reduced when treated with 62 g ha^{-1} benzobicyclon compared with the nontreated. Indian toothcup biomass was also reduced compared to the nontreated when treated with 185 g ha^{-1} benzobicyclon. No differences were observed in fresh weight biomass of barnyardgrass, yellow nutsedge, purple ammannia or false pimpernel. The reduced activity on these species may be explained by the large size of the weeds when applications were made; however, these data suggest benzobicyclon would be a control option for mid- to late-season ducksalad or Indian toothcup infestations in rice.

Glasshouse trials were conducted at the Louisiana State University campus in Baton Rouge, Louisiana in 2013 and 2014. Five yellow nutsedge plants were germinated in 50-2.5 by 2.5-cm cell growing flats and transplanted into 38-L Rubbermaid® containers that were designed to hold either a 5- or 10-cm flood. Plants were allowed to establish for 7 days before benzobicyclon was applied at 0, 246, 493, 984, 1476, and 1968 g ha^{-1}

with a 5- or 10-cm established flood. Yellow nutsedge visual control was evaluated 14, 21, and 28 DAT. At 28 DAT, plant height was measured from the soil to the tip of the most extended leaf. Following the last visual evaluation and height measurement, plants were removed from soil and thoroughly rinsed and blotted dry. The number of tubers and leaves per plant were determined, and the above ground plant tissue was separated from the below ground tissue and fresh weight biomass was obtained for each.

Yellow nutsedge plants treated with benzobicyclon at 493 g ai ha^{-1} were 42 cm in height and shorter when compared with the height of nontreated plants; however, no difference occurred for plant height, 47 to 51-cm, with yellow nutsedge treated with any other benzobicyclon rate evaluated. Yellow nutsedge treated with benzobicyclon at 246, 493, and 1968 g ha^{-1} reduced below-ground fresh weight and total fresh weight compared with the nontreated. Yellow nutsedge plants receiving any rate of benzobicyclon had fewer tubers than nontreated plants, and because yellow nutsedge primarily propagates through tuber production (Stoller and Sweet 1987), benzobicyclon could be useful in reducing future populations of yellow nutsedge.

Two studies were conducted in 2013 and 2014 at the RRS to evaluate benzobicyclon mixed with imazethapyr or imazamox herbicide in imidazolinone-resistant rice (IR). In the first study, imazethapyr was applied as a two-application program and benzobicyclon was mixed with one of the imazethapyr applications at different timings. In the second study, imazethapyr and imazamox were applied as a two-application program and benzobicyclon was mixed with either imazethapyr or imazamox at different timings. The entire plot area was treated with herbicide and 91-cm diameter by 30-cm tall galvanized metal rings were placed near the center of the plot and pressed 5-cm into the soil for benzobicyclon treatment containment. Visual control ratings of hemp sesbania, yellow nutsedge and barnyardgrass were collected

14, 28, and 42 DAT. At the conclusion of the study the center four rows of each plot were harvested with a mechanical rice harvester.

Imazethapyr applied early-postemergence (EPOST) at 105 g ai ha^{-1} fb imazethapyr applied LPOST at 70 g ha^{-1} controlled barnyardgrass 86%. The addition of benzobicyclon did not increase barnyardgrass control over the imazethapyr only program when applied prior to permanent flood establishment. Barnyardgrass control decreased by delaying the second imazethapyr application to a POSTFLOOD timing and the addition of benzobicyclon POSTFLOOD did not increase control of barnyardgrass compared with the imazethapyr only program. A slight increase in hemp sesbania control was observed with the addition of benzobicyclon applied with the EPOST or LPOST imazethapyr timing; however, control of hemp sesbania was below 30% for any mixture evaluated.

Imazethapyr at 105 g ha^{-1} applied EPOST followed by imazamox at 44 g ha^{-1} applied LPOST controlled barnyardgrass 90%, and the addition of benzobicyclon did not increase barnyardgrass control over imazethapyr applied EPOST fb imazamox applied LPOST, PREFLOOD, or POSTFLOOD. A decrease in barnyardgrass control, 66%, was observed by delaying the imazamox application to the PI timing, and the addition of benzobicyclon at the PI timing increased barnyardgrass control, 72%, to levels observed with imazamox applied POSTFLOOD. An increase in hemp sesbania control was observed when benzobicyclon was mixed with any imazamox timing except when applied at PI, but this increase was slight and hemp sesbania control did not exceed 30% from any herbicide treatments.

In both field studies no differences in rough rice yield was observed for any herbicide treatments, suggesting the addition of benzobicyclon, with the weeds present in these studies, to imazethapyr and imazamox programs in IR rice does not increase yield from enhanced weed control activity; therefore, alternative mix partners with increased activity on hemp sesbania may be an option in IR rice.

Weeds that are resistant to herbicides have been identified in recent years, and several of these populations infest rice in the U.S. Single and multiple mode of action resistance has been documented for populations of barnyardgrass and *Cyperus spp*. (Baltazar and Smith 1994; Carey et al. 1995; Heap 2017; Malik et al. 2010; Norsworthy 2009; Wilson 2011). Rotating herbicide mode of action can be an important component to a resistance management program (Norsworthy et al. 2012). Benzobicyclon is a HPPD inhibitor and this mode of action is currently not labeled for use in U.S. rice production. Benzobicyclon applied early in a water-seeded rice on small actively growing barnyardgrass immediately following the establishment of the permanent flood could be utilized as a management option for barnyardgrass populations resistant to other modes of action.

Ducksalad is often an early-emerging weed in water-seeded rice (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). This research evaluating benzobicyclon application timings in water-seeded rice have demonstrated that benzobicyclon has excellent activity on ducksalad occurring in these production systems when applied immediately following the permanent flood establishment. Benzobicyclon also has activity on larger ducksalad that can become troublesome mid- to late-season.

While benzobicyclon does not provide complete control of yellow nutsedge at any of the evaluated rates, the glasshouse study conducted demonstrated the activity of benzobicyclon on tuber development. The primary means of yellow nutsedge reproduction in the U.S. is through tuber production (Stoller and Sweet 1987). By reducing tuber number, benzobicyclon treatment could affect future populations of yellow nutsedge.

These data indicate benzobicyclon could be an effective herbicide option for the control of certain troublesome weeds in Louisiana rice production when applied under the right conditions and in a timely manner. The unique water activity characteristics of this herbicide are well adapted to the water-seeded production system, which accounts for a considerable portion of planted rice area in Louisiana. These data demonstrates the activity of benzobicyclon in different rice production scenarios, and it will serve a role in aiding future weed management decisions in Louisiana and U.S. rice production.

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